LINKING MPBN AND SYSTEM OF SYSTEM THINKING:

TO IMPROVE OUTCOMES IN URBAN ENVIRONMENTS USING CHINESE WORKER VILLAGES AS A TEST CASE

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By

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Sincerely, Thank you

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SUMMARY

Urban environments are composed of a multitude of systems that actively engage with each other to maintain, grow, and define the physical forms of the city. These individual aspects can be divided up into a series of system trees that form distinct entities, but together they corm a complete matrix of systems that influence and affect the urban context. These systems fall under two significant categorizations of flows either those mostly affecting the physical world and those that are more confined to the virtual or non-physical world. Often the boundary between these two systems, or elements within them, are not neatly contained to themselves as they intermingle and create uncertain and stochastic edgeless systems. This paper is to focus on the coupling of the **M**aterial – **P**roduct – **B**uilding – **N**eighborhood system, and the system-of-systems thinking for logistical systems for a single material pathway.

Chapter 1: Introduction

Urban environments are a consequence of the complex interaction between systems and actors which actively engage to: maintain, grow, and define the physical and non-physical flows and forms of a city. These systems can be sub-divided into a collection of system trees forming discrete entities, but together constitute a complex matrix of systems that influence and affect each other and the urban context. These systems fall under two general categorizations of flows; those primarily affecting the physical world and those describing the virtual or non-physical flows of the world. Physical flows, in the urban context, refer to the transfer of energy, material, water, food, CO_2 and other flows resulting in the movement of physical entities. Included are those flows that have a direct effect upon the physical context by their transmission or movement and these forces have spatial dimension to them. Non-physical (aspatial) flows are those cultural, political, logistical, information, data and entities that are not physical, but have an indirect effect on the urban context and alter the city's use patterns (Batty, M., & Cheshire, J. 2011).

Often these two forces work in concert with each other resulting in an edgeless boundary condition between them. As these two meso-systems or the elements within them are not neatly contained to themselves as they intermingle creating an uncertain and stochastic edgeless dual system. These flows and complex interactions are at the heart of urban systems and urban planning. However, the complexity of these meso and macro (down to the micro) scale system trees, in their entirety, are beyond the scope and resource constraints of this thesis. Instead, they form the backdrop upon which a micro evaluation and linkage between the subsetted MPBN system and its logistical tree partner are conducted (Yang, P. P., et al., 2017). The purpose of this paper is to focus upon the linkage of the MPBN system and the use of system-of-systems thinking for logistical systems by careful examination of a single material usage pathway applied to an actual test case location.

The driving force behind undertaking this study and the framework proposed via its completion is the evaluation and application of system-of-systems to mimic the complex stochastic network of choices that affect the urban environment. Moreover, how choices can be improved by viewing them in their entirety instead of as composite parts. Despite the close and integral relationship existing between the urban environment and the materials, products and buildings used to construct them most research has concerned itself with only single system level interactions, from product to building or material to product. Progress has been made studying component parts of these systems and the logistical transformation that they undergo as steps in the urban process, but presently a concise evaluative framework for the inherent complexity is lacking.

The focus of this research is a holarchical view of systems in which individual elements of the system comprise complete and independent systems (Koestler, A. 2016). Regarding this paper, holarchy defined as the as-built sector comprised of four major unique systems which each maintain their coherent characteristics and structure while simultaneously being interconnected. Materials, Products, Buildings, and Neighborhoods (MPBN) are the four key elements of the MPBN system which when analyzed provide insight into the complexity of the urban structure (Yang, P. P., et al., 2017). Coupled with the MPBN system analysis is the logistical tree that when parts are transferred from one segment of the holarchical system to another that any energy consumed is embedded into the materials and final products during this process. For example, a metric that could be attached to this evaluation, but beyond the scope of this investigation, is the ability of carbon to be measured, captured and reused internally (or externally) to the process – often referred to as Carbon Productivity (McKinsey Global Institute 2008). This method views carbon, not as a waste product, but as a resource that when applied efficiently further reduces carbon expenditures in other areas. Carbon Productivity, although useful for informing the topic, is not included in this analysis of the urban system.

Essential is the applicability of this approach not only from a theoretical framework perspective but to real-world applications. To better illustrate, a real-world test case is employed aided by construction of synthetic individual elements, to test the savings and ability of the framework to cope with real problems.

By struggling through the primary consideration, joining building simulation (from material to neighborhood) and logistical systems, the two primary contribution of this work and the author are the adding of value estimation to the system linkage and tying energy to the logistical components. Previous logistical research has considered cost in terms of time and monetary cost, but this research adds to this conceptualization by adding energy and CO_2 considerations to the synthesis of the logistical and building combined modeling. Although the data used is specific to the Chinese context and case study certain generic elements and the methodological framework can be applied to other locations and large scale projects. As this work connected two disconnected, but associated elements, of logistical analysis and building energy modeling.

1.1 Background and Primer

There are four general concepts which inspired the primary objective of this study: System-of-Systems, Complex Interconnected Stochastic Edgeless Systems, Creating Modular Urban Systems and the MPBN System which each of these elements helps to influence and create a better urban framework. System-of-Systems mimics the complex manner in each urban flows and systems operate, as connected entities that are complete systems of themselves. However, these systems form a nested hierarchy within a broader context and generate the macro level systems that influence the dynamic urban environment. Each element contained within the systems (at the macro or micro level) that has a direct (or indirect) impact on other parts of the larger system interconnected with positive and negative feedback loops. This vast matrix [interconnected network] of individual and collective decisions is what forms the basis for problems and solutions to cities and urban environments (Yang, P. P., et al., 2017).

This inherent complexity leads to the second driving force behind this research; Complex Interconnected Stochastic Edgeless Systems. In studying systems and their effect on the urban context and greater environment, boundaries are often created to make the study of an object manageable and workable within that context. However, most of these system boundaries are abstractions of real-world conditions that in large complex systems often lack a precise boundary or edge conditions across all parameters (Wilson, A. G. 2012). Despite this, it is necessary to assign discrete limits to model something otherwise it becomes unattainable to manage the level of complexity found in reality. At the same time, each level of abstraction makes any application more complicated as the lessons and findings from a particular study maybe outside the context it was designed for as noted by general or specific test cases.

From this dilemma, a third element arises, the creation of a modular set of urban systems which attempt to represent a more accurate picture of the real-world conditions that can be improved and replaced as time moves forward. Creating not a solution for a point in time, but a continuous process to be modified, studied and expanded as ourunderstanding increases that is not reliant on starting a complete cycle over again. That by continuous monitoring, engagement with technological innovations, and using computing tools yields a better understanding of how elements influence each other. This method does not create ideal solutions but instead generates a moving design space that helps to inform business, builders, planners and alike in what trade-offs can occur and how best to use the limited resources of the city. Incorporated into this idea is the fundamental notion that urban systems have been traditionally reactive to larger forces, but as technological changes continue to accelerate faster than societal and even individual understanding, it becomes increasingly necessary to reduce this gap and strive towards a proactive city. An urban context that is active in its evolution and interaction with the population that directly interfaces with it, and the more extensive regional (or global) interactions between these cities and people themselves.

In doing so, it becomes necessary to conceive of the problem first in its smaller interconnected elements and expand the system upwards and outwards as pieces are proven as a framework, which is where the MPBN system becomes of critical importance. The MPBN system is the first part of the broader context and examines the relationship between materials, products, buildings, and neighborhoods as an interactive set of systems that work both ways. Relevant to this is not just the individual elements contained in each, but how they transform and are moved from one part of it to the next, meaning logistics plays are a necessary component as well. These elements form the first steps towards the study of the larger system and hopefully a better understanding of the urban context and elements that make up its constituent parts.

1.2 Defining the MPBN System

Before an exploration of these complex systems, or the questions at the core of this paper, can be examined a working definition of what constitutes the MPBN system, must be given. The MPBN System is a relatively new concept in the field of urban science concerned with understanding the relationship that **M**aterials, **P**roducts, **B**uilding and **N**eighborhood have to each other and their consequences (Yang, P. P., et al., 2017). The premise is based upon the idea of Holons and Holarchy as termed initially in Greek philosophy and reiterated by Arthur Koestler in his book The Ghost in the Machine, which states: “A holon is something that is simultaneously a whole and a part” (Koestler, A. 2016). A significant aspect of holons themselves is their self-reliance and autonomous behavior that enables them to act independently of each other, while still coming together to form a greater whole. Originally used to describe natural systems, such as how organelle in a cell function independently of each other, but still operate in a context of the others to construct the larger organism that is the cell. This multi-layered system of independent, yet connected, nodes (holons) operates in the realm of a hierarchical system (a holarchy) which can go from fine-grain systems like atoms to macro level in the study of biology (Koestler, A. 2001). Through this understanding of the natural world comes a more refined understanding of the way systems interact with each other and form a more interconnected network of Systems of Systems.

These ideas were expanded upon by Thomas Graedel and Braden Allenby and applied to the field of industrial ecology and engineering. In their book *Industrial Ecology* they describe that the creation of materials is the result of a nested process of holons that take a feedstock (inorganic or organic) and transform these raw resources into workable resources. These finished resources are then taken and used to produce the material components that are then readily used to generate final products (Graedel, T. E., & Allenby, B. R. 2002). However, each material does not serve one specific product, as products do not have one destination or end use, and form a network of decisions and system-level interactions that influence each other. These interactions both feed upstream and downstream from the level upon which they occur leading to additional demand, supply or resource allocation that spawn more sets of interactions. Within this broader context studying these elements, not only within the individual system where the initial expenditure occurs, more efficient and resilient systems will be created and subsequently improved.

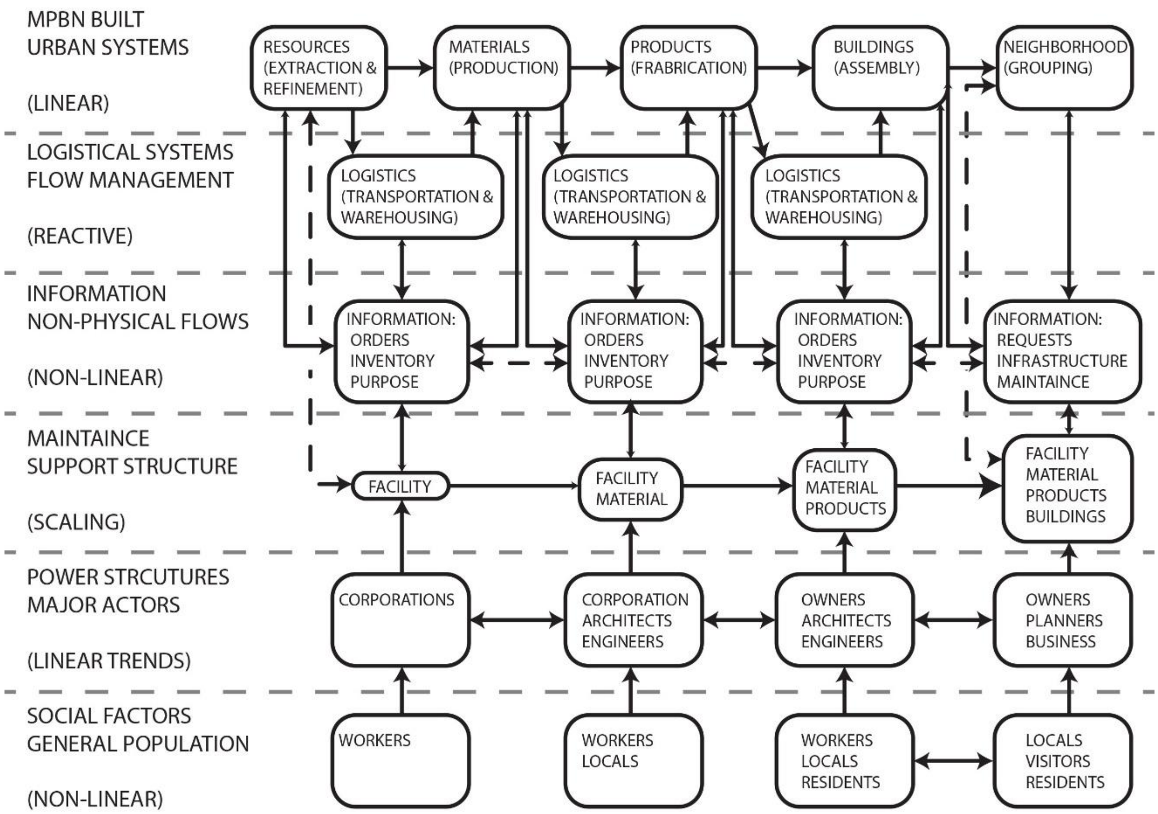

Figure 1: Urban System-of-Systems Research Design

Based upon this concept a larger framework of the entire urban system parts can begin to be conceptualized in a complex and (in)complete manner. Figure 1 above shows an initial framework of the stochastic systems engaged in the urban context and how they influence each other in multiple complex interactions of backward and forward integration. These layered systems are broken down into several parallel tracks that each has a number of different holons active interior to them. In this large system are the built and building systems used in the creation and extraction of resources and eventually used in the manufacturing of cities themselves. Logistical systems move materials, information and various elements around internal or external to each system. Use and Development help design the function of space and sees it as used, maintained, renovated or eventually recycled/destroyed. Social and political systems influence what is built in terms of laws, building codes, and accepted fashions, models, or ideas proposed at the time in which something is constructed or evaluated. Several others which are yet to be studied and expanded upon, are left open to make the complete system extensible enough to receive new ones as they become known, studied or quantified.

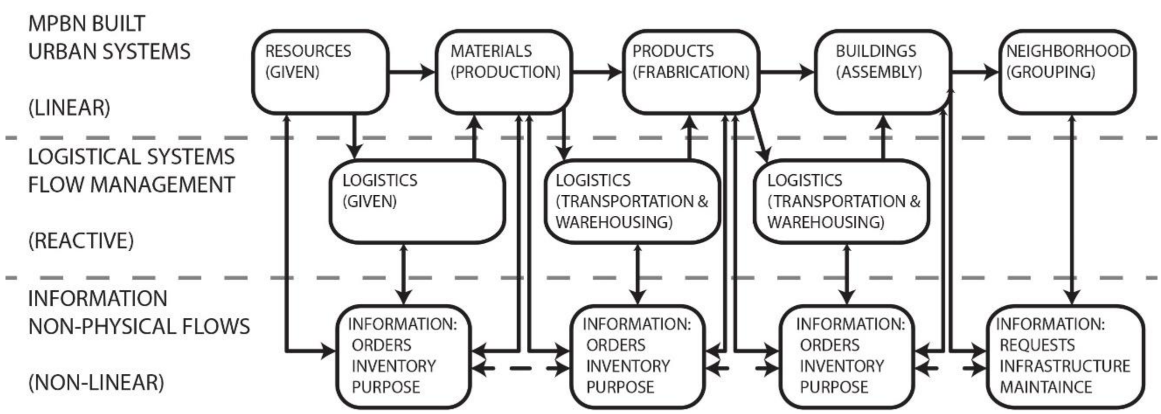

Figure 2: MPBN Research and Logistics Design

This complex collection of systems in its entirety is beyond the scope of a single study, and an individual constituent part is the key focus of this study, integrating the logistical component with the building aspects concerning its influence on the urban scale. To accomplish this, a focused area of the entire system will be examined, as shown in Figure 2, which narrows the system down to the Material, Building, Neighborhood and logistical analysis. It is this narrowed focused approach that will be applied to the real world practical case and work through the major elements of the MPBN system.

It is upon this foundation that the MPBN System was developed in previous studies by Perry Yang, Yihan Wu, Steven Quan and Michael Tobey at the Sino-U.S. Ecological Urban Lab. As stated previously, MPBN is an acronym for the four major components that comprise the actual system itself:

Materials: Form the lowest level of studied system inputs and are the finished materials that are then used to create products and not considered products themselves for this study. This category includes materials like polyurethane, polycarbonate, and substances similar to them.

Products: Are elements that are constructed out of materials and sold to contractors or users for use in buildings or their construction. This classification includes; windows, insulation, tiles, flooring and any finished products used in the construction of buildings.

Buildings: Are defined as structures, made up of assemblies, divided up into different types of land use functions and typologies: such as office, residential and commercial.

Neighborhoods: are assemblies of multiple buildings together to form a coherent urban space.

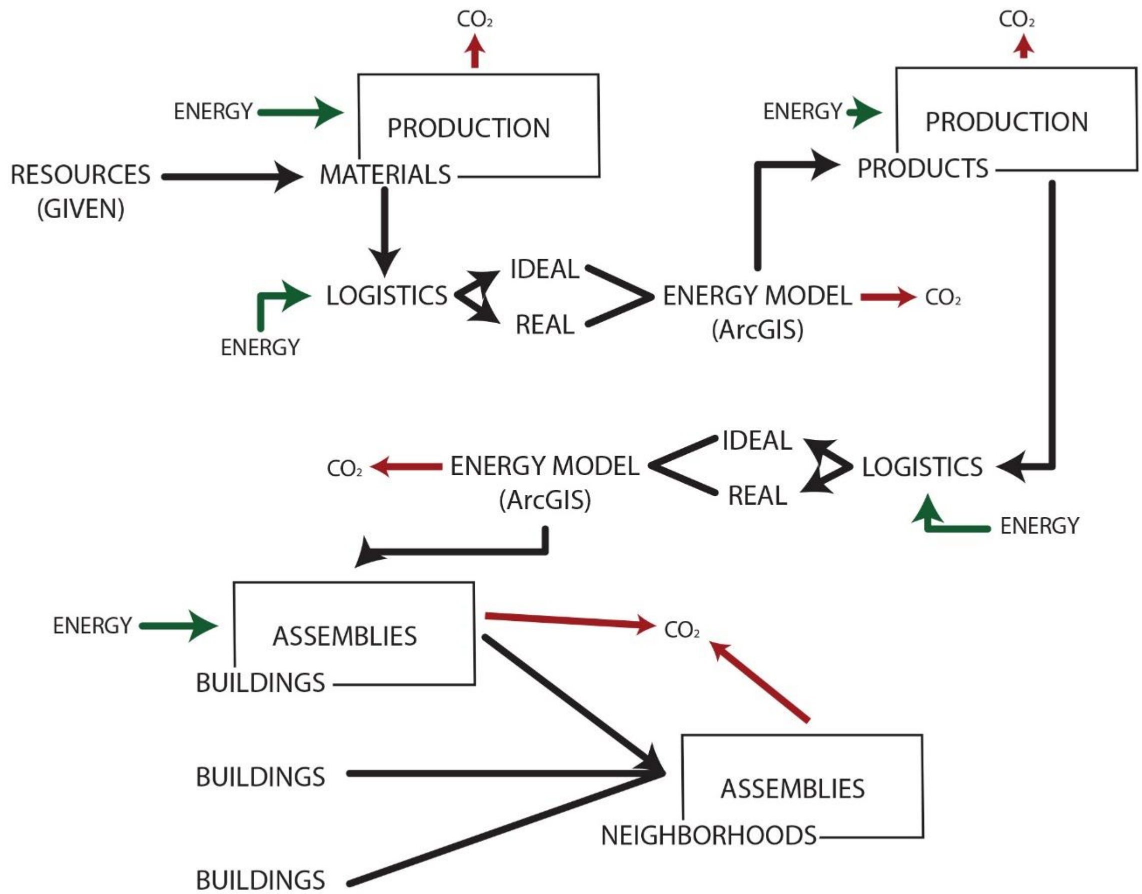

Figure 3: MPBN Energy and Relationship Mapping

Although forming the conceptual framework of the modeling system, there are a total of seven component parts used during an MPBN analysis. (1) Resource/Raw Input, initial inputs fed into the system to create materials and are abstracted at this stage. (2) Material Modeling is the transformation and processing of resources into final materials that can then be used to create products. (3) Product Fabrication examines the process by which materials are made into products through studying the compounded labor costs in addition to their emissions. (4) Assembly Construction is used in the study process in applying products into their assembly that are erected to make buildings like walls, roofs, and floors. (5) Building Erection takes the embodied energy that has been put into the materials and products at every stage and gives an energy value for the total cost of the building in terms of monetary, energy flows and labor. (6) Neighborhood Development looks at how the combination of buildings affects the urban context and work together to form a more or less efficient environment. (7) Transportation and Logistics examine how materials, products, and elements are used to move from one point in the system to another and impart energy into those elements (Yang, P. P., et al., 2017).

1.3 Logistics, Supply Chain, and System of Systems

The initial development of the MPBN System did not include the final portion of the analysis "Transportation and Logistical" analysis and is an additional component considered by this study. As such, an explanation of this system is necessary, as unlike the other aspects of a system this one occurs between each step and adds extra costs and externalities to the system. Most energy and modeling studies that consider logistical analysis are centered around the instance in which it occurs or between the single steps being considered for the study (Al-Homoud, M. S. 2001). Even when considered as an element in a supply chain study this is studying the given nature, or the prospective nature of a different study, a single material or product chain, not always within the larger context (Crawley, D. B., et al., 2008). Therefore, this study seeks to expand on both of these through the inclusion into the MPBN System which is designed to function as a system of systems that allows for modular adjustment of component parts considering the entire life cycle and value chain of each part, not in isolation, but as a whole.

For this, each of these terms will be given greater detail to understand the terms and their usage within the context of the paper and the study itself. For the purpose of this study, logistics refers to the process of transporting goods, by any means, from one facility to another between major transformative processes. Within this large logistical umbrella falls the truck itself, the labor-hours required to operate it, the mode of transportation, logistical facilities and anything related or supporting this process. Based upon professional interviews and questionnaires a logistical facility is separate from the material production and product fabrication facilities in that these are places used to store goods typical and can be either run by the primary part, onsite or operated by a third party logistical company (Covestro 2018).

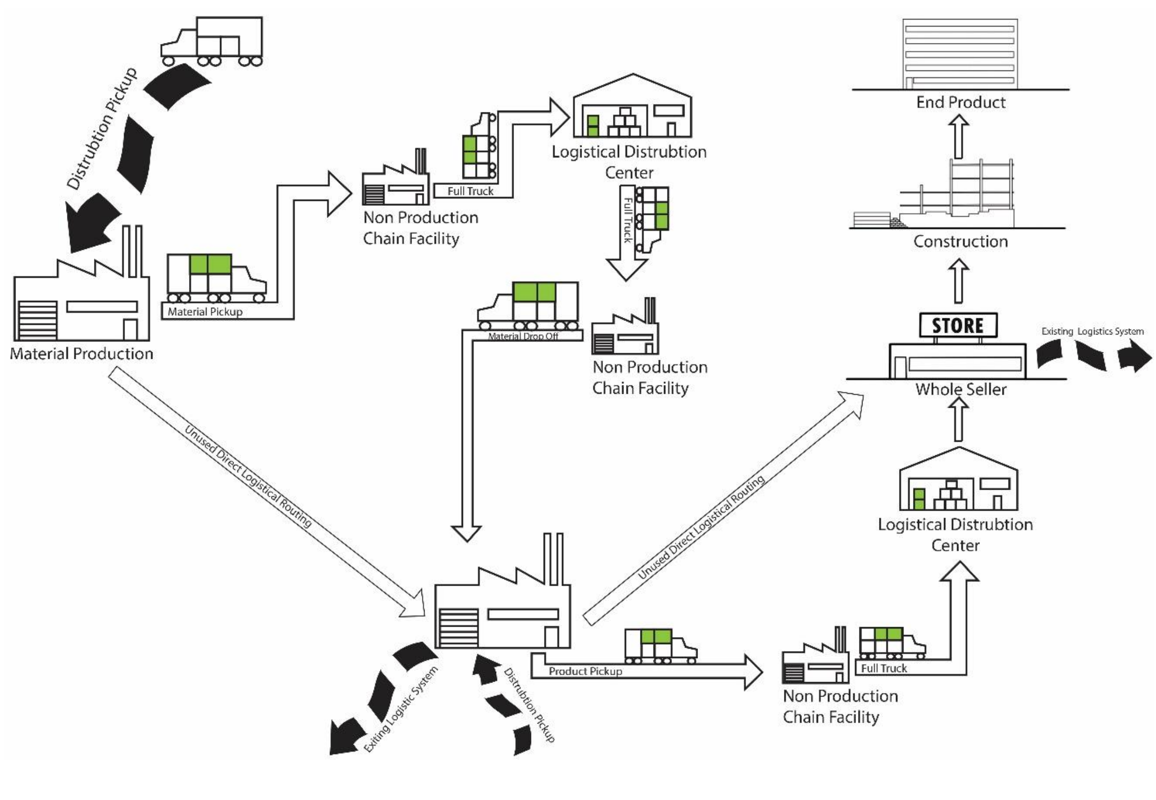

Figure 4: Realistic Logistical Model

There are two significant ways to model the logistical aspect of the built system either the ideal way (Figure 4) or the simplified way (Figure 5). For the purpose of this study, a simplified approach is employed because the amount of data (often proprietary) needed to construct accurate location and distribution routes required for the ideal model. The ideal model works for either direct control (company owned) or indirect control (third party system) of logistical analysis. The model needs to know the locations of each facility involved in the pick-up and delivery of goods both from the primary material studied, but also those factories or locations visited after (pick-up) and before (drop-off) when delivering goods. Beyond this, modeling requires knowing the logistical centers where goods are stored and repackaged, though this method is more frequently used in the indirect logistical control model. This ideal construction was developed with the help of research and data analysis from corporations and interviews conducted with them (Covestro 2018).

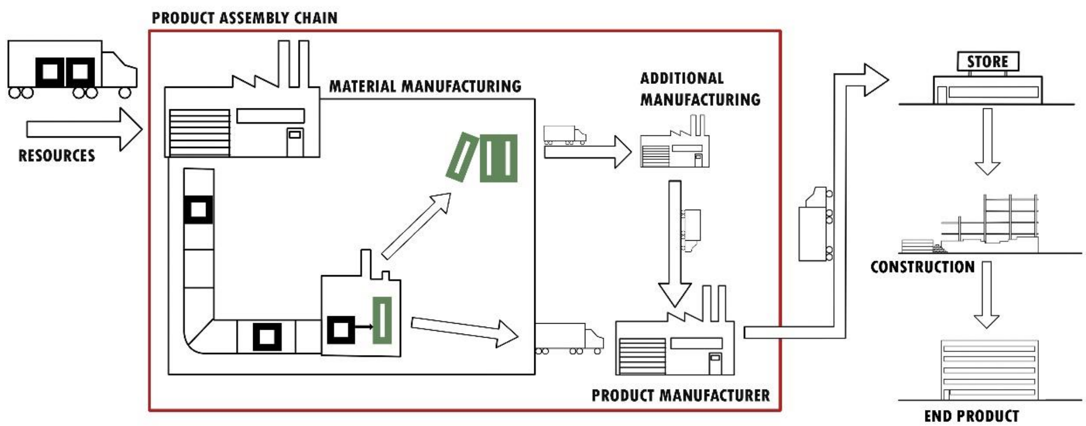

Figure 5: Simplified Logistics Model

As stated previously, the actual logistic model employed for this study will be the simplified version which does not contend with the complex interactions of secondary facilities and additional logistical drop-off facilities. Instead, it is primarily used to study direct logistical chains where materials are delivered directly to the product manufacturer. Once transformed into products these are then shipped to a wholesaler’s warehousing facility, before heading to the storage and ultimately the construction site. Although a direct logistical model is not always used, especially in countries like China, it does provide a best-case scenario testing for examining a material (outside the context of the complete urban system).

Supply chains, and by process their larger value chains, are connected to logistics and this extended level of systems studies. This result stems from supply chain management (SCM) managing the flow of goods and ultimately revolves around the movement, transformation, and storage of goods, products or materials (Iyer, A. V., et al. 2009). In this way. MPBN deals directly with the supply chain of a specific good in question, or to all products and materials below the highest level of the study – dependent if used as a top-down (from M to N: Many to One) or bottom-up (from N to M: One to Many). Value Chains are an additional component that can be added to supply chain. Where supply chains deal with the movement of goods themselves and how they interact, value chains are the process by which something adds value (Christopher, M. 2011). Typically, value is measured in a monetary format, but for this study, this metric can be extended to the environmental impact as a cost using energy and emissions.

Combing all of these systems together along with the construction of the MPBN system itself is the concept of System of Systems, or that objects reside in a nested hierarchy comprised of complete and independent parts that form even more complex systems (Maier, M. W. 1998).

1.4 Purpose of the Study

The central objective of this thesis is to explore the core concept of linking complex system level theory, along with supplemental questions developed through the research process, to urban development and the fundamental building blocks that constitute it. Thus, the goal is exploring the connection between materials, products, buildings, neighborhoods and their accompanying logistical components to come to a better understanding of their interactions. In addition, laying the framework and foundation for a modular urban system that can contend with the multifaceted issues of stochastic systems in cities.

This consequence results from the lack research centered on investigating the linkage between these systems and their interactions. Currently, considerable research has gone into studying the individual parts of this system including numerous modeling software and programs designed and developed to look at discrete parts. These are present in the simulation of buildings in BIM, Revit, Ecotect, EnergyPlus, ArchSIM and other energy modeling software that examine the effect of buildings and the products used in them (Crawley, D. B., et al., 2008). GIS has been used extensively for neighborhood analysis as well as logistical analysis providing spatial dataset computing capabilities (Wang. Y., et al., 2008). The U.S. Government publishes software exploring the transformation of materials into products (mainly from raw resource to fuel) and how they are transported (Argone National Laboratory 2017). However, despite these individual approaches, a unified framework or a way of dealing with all these parts simultaneously is still lacking. It is this fundamental premise that has spawned the purpose of this study and examining the interconnected nature of all these elements contained within the urban context.

1.5 Research Question

The core question presented, and examined, throughout this research focuses on the integration of the logistical (ArcGIS) modeling design can be linked and combined with the MPBN system (Rhino/BIM) can be used to create urban outcomes. Through the study and evaluation of energy, emissions and costs (monetary and other metrics) following a single material through the entire urban process the embodied energy, and alternatives, can be compared against the baseline energy model. Simplistically this forms the following question: Does examining a material, and its alternatives, within the greater context (recursively through all elements examined during the study) lead to lower emissions, better energy use, and a more accurate picture of the cost caused by a particular material applied to an urban context. This study examines a single material, with the ability for the system to be expanded upon to deal with multiple materials and decision trees in the future. It will also be using data and buildings developed in China with the testing of the general framework which is modular enough to be modified to the specific context in which it can be later applied.

Linked to this core question are a number of other issues and potential questions that could be asked or investigated, but are outside of this study. Carbon Productivity is among these, and one of the major ones, which deserves mention, but is not considered in this investigation, because of resource constraints. Carbon Productivity is an alternative way to view carbon and its place in material and product generation, not as a waste by-product, but a resource to be recycled and used effectively. In changing this perspective, one can see how to use carbon in specific products to reduce greater carbon expenditures elsewhere and view it proactively (McKinsey Global Institute 2008). This important issue is one that will be included in future iterations of this research but not included in this version. Below is a list of the series of sub-questions to be investigated throughout the study: The effects of the logistics supply chain in the energy impact on materials and products used in the construction and building industry.

1.6 Expected Results

Based on the research question and by the process the sub-questions linked to it, there are three principal objects of this project. (1) Expansion and creation of an initial urban complex systems framework that is modular and dynamic enough to be applied to existing systems initially limited to the as-built environment. (2) Linking embodied energy of logistical processes for material transformation to buildings with the energy savings and cost used in the creation and erection of these materials and products. (3) A more accurate decision modeling system that with sufficient data can be used with direct industry application to make better materials, product, and urban choices through linking logistics with buildings. These three objectives together help to create a better urban environment for people and nature is the combined ultimate goal of the paper.

These objectives and expected results form a vital part of the paper by the creation of a usable framework, which is more than theory, having a practical application for use by industry professionals, builders, designers, planners, and manufacturers. It is crucial for the modern climate to increase cooperation and link trades together in a manner that promotes sharing data to make more informed decisions that are interconnected. Although the decisions made by one part ultimately affect the others, they are rarely studied using this approach as an entity refuses, or is reluctant to go first, to participate in a system that requires a new paradigm based on openness and symbiosis (Iyer, A. V., et al. 2009). Recently, there are business and corporations that have realized this need to work together in a more integrated manner. One that examines the interlinked nature of decisions at the urban scale, and it is for this purpose that the research focuses on an applicable system.

For this framework and practical element to exist the theoretical underpinning is needed, and a proof of the framework is necessary, which links each of the expected results together. Although this paper relies on the base development of the MPBN System Theory it also examines, or rather questions, the larger context of the system in which this exists. Forming the underlying foundation upon which future systems and modular elements are constructed. It is this theoretical and conceptualized system that isexpanded upon via this research and continued in future work and studies into the urban systems and the forces affecting it.

Finally, and most importantly, by aggregating these goals together the ultimate end is to improve the current conditions in the world today, and the future, by generating better and smarter choices. The research serves both to enrich the understanding of the complex stochastic systems at play in the human ecosystem of the urbanity. While also generating a process by which these understandings can be translated to direct uses that result in better outcomes.

1.7 Paper Outline

This paper is divided into seven chapters and contained within three overarching sections: Setup, Analysis, and Conclusion. The first section Setup contains the first three chapters: Introduction, Methodology, and Literature Review and sets up the framework for the study. **Chapter 1:** Introduction lays out the purposes of the paper and key definition of terms and analysis used throughout the entire paper. Included in this is layout the primary research question governs the paper and is ultimately answered by it. **Chapter 2:** Methodology details the process by which the research was conducted and the limitations of the study itself. Presenting the scope of the study, data analysis and the selection reasoning for the test case. **Chapter 3:** Literature Review breaks down the primary sources into the four main categories of study that influenced the nature of the work. These include Supply Chain Management, Urban System and Energy and Emissions Modeling.

The Analysis section contains two chapters: Data Collection and Analysis and Testing. **Chapter 4:** Data Collection details the sources and methods used to collect the baseline data for simulation. In this chapter, the modeling assumptions and creation is laid out to delineate the primary test cases from the baseline (no change) to the change model (material study). **Chapter 5:** Analysis and Testing run through the modeling procedure and direct outputs. The measurement of the amount of energy consumed, emissions and material cost comparison. The modeling approach uses two main software types to conduct the analysis Rhino, employing Grasshopper Plug-in along with ArchSIM and EnergyPlus, and ArcGIS to route the logistical pathways.

Section three Conclusion has two chapters: Findings and Results, and Conclusion to summarize the entirety of the paper. **Chapter 6:** Findings and Results summarizes the results from the previous chapter and section into useful statistics and understandable data. Listing key findings that can be applied going forward and towards future studies along with real-world applications. **Chapter 7:** Conclusions lays out future plans for research, limitations inherent in the study, and what should be taken away.

Chapter 2: Methodology

This section details the methodological framework that was followed in order formulate and answer the research question that is at the core of this study. The methodology was developed to follow a basic structure through which key aspects and concepts were easily identified and understood. Figure 6 displays the analytical method used throughout this research.

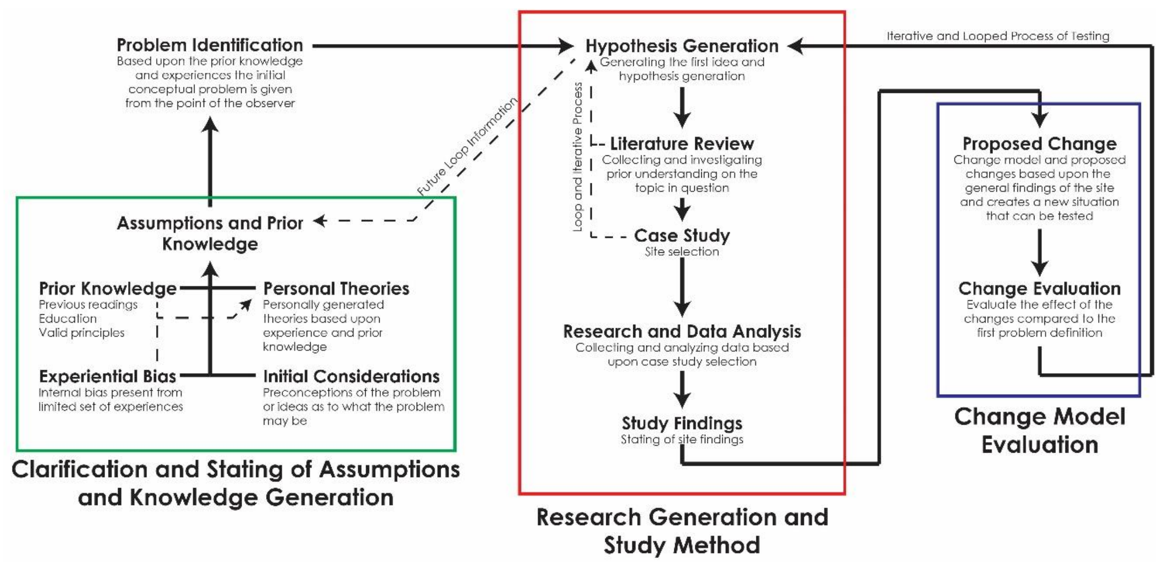

Figure 6: Research Design

Based on the above framework the research is divided into six major sections, with subsections contained within them, addressing the issue from prior to the identification of the issue to the completed end result. Each of these core aspects will be given a cursory overview in this section, followed by further detailed explanation later in this chapter. **(1) Assumptions;** are those inherent assumptions of the author that are introduced into the subject matter and those data assumptions necessary to complete the evaluations. **(2)**

Hypothesis Generation; through observation of a problem, logistical and building energy modeling, that combines with base assumptions the process of hypothesis generation occurs to develop an initial question. **(3) Literature Review and Question Refinement;** external information is studied to test base assumptions and ideas in the formulation of a final research question. In addition to external sources contained within literature outside experts and academic advisors were consulted in refining the final question. **(4) Case Study Selection and Data Collection;** three possible test sites for which data could have been collected are scattered around the world in Tokyo, Japan; Shanghai, China, and Atlanta, Georgia in the United States of America. The case study and data collection process details the means by which one of these was selected, ultimately Shanghai, China, and the collections methods used to get data. **(5) Analysis and Testing**; following the complete data collection process the test case will be evaluated and run through the primary research model to determine the change when applying the test parameters to the case. **(6) Evaluation and Conclusion;** finally, the various solutions and cases that were run will be compared and an evaluation of each quantified. Contained in this is also the conclusion and final findings of the study and what can be done or changed in future installments and iterations of the study.

2.1 Assumptions

Assumptions and prior knowledge form the base background behind this study as well as inherent bias and impetuous of the initial quandaries that resulted in the selection and exploration of this topic. Beyond the base assumptions of the individual researcher, many of which have been detailed out throughout the introduction, several data assumptions are made to complete the study. Although this project uses data and framework developed in previous research work for Covestro, a partner of the Eco Urban Lab, the data used for this project is generalized to alleviate bias of potential data issues. Inherent in this assumption, the actual production facility locations, for materials and products, are not used, but rather average logistical distances to create realistic synthetic locations based in the Shanghai area. Secondly, all buildings within the case study area will be assumed to be the same typology and structure, based on selection and investigation process are created parametrically. Third, to calculate the emissions of production and transportation the standard Shanghai power grid will be used, except in cases where renewable energy data was collected and applied to the energy consumption rate. All material delivery, as well as products, use the simplified logistical model and eventually reach the sole location of the study, with different locations explored in future iterations of the study. Finally, all building material and product data will be considered generic and held constant for this study to judge the difference between logistical and material changes in the built environment.

2.2 Hypothesis Generation

The general hypothesis generation process occurred during the first three weeks of the study following an iterative design and creation process (Figure 7). This stage of the research revolved around detailing out base assumptions that influenced will or could influence the study and the author's interpretation of the problem. These were then balanced with the outside advice of experts and practitioners study the subject, and who understand the nature of the field and possible case study locations. The general outline of this process that underwent several iterations is noted in the figure below.

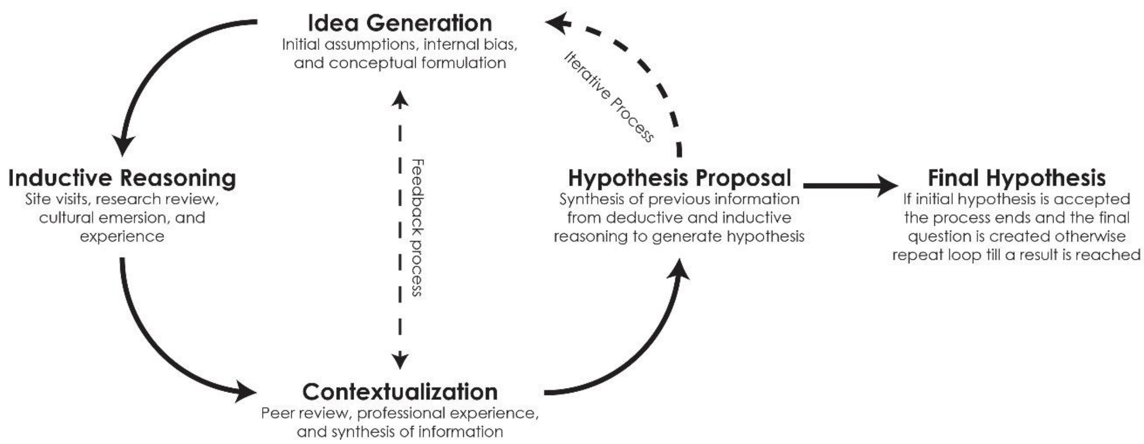

Figure 7: Hypothesis Generation Process

The figure shows that idea and hypothesis generation process is an iterative process that begins after the formalization of assumptions and prior knowledge, to provide better guidance to the direct the study. The process begins at the top idea generation that serves to create concepts of how to contend with the noted issues, in this case, the ability to study the complex interactions that occur throughout the building and construction process as pertains to the urban fabric. Following the initial idea generation, the next involved a base literature review in developing a better understanding of supply chain mechanics and the forces involved in the material to the building process. Although this allowed an academic understanding of system mechanics, it became essential to balance this against the real constraints and forces at work in an actual logistical system. Relying on experts from the logistical supply side and through interviews conducted with a corporation, as often logistical data is kept a closely guarded secret, was used to provide a baseline understanding of the actual mechanisms involved in these complex nested systems. Using the knowledge acquired during this process, an initial hypothesis was proposed and brought forth for review by the advisory committee and criticism provided. At this point, the iterative nature of the process begins depending on the comments, and critiques of the initial hypothesis and one of two outcomes occur: (1) hypothesis is defensible and adequate or (2) it is in need of further revision, and the process must begin again.

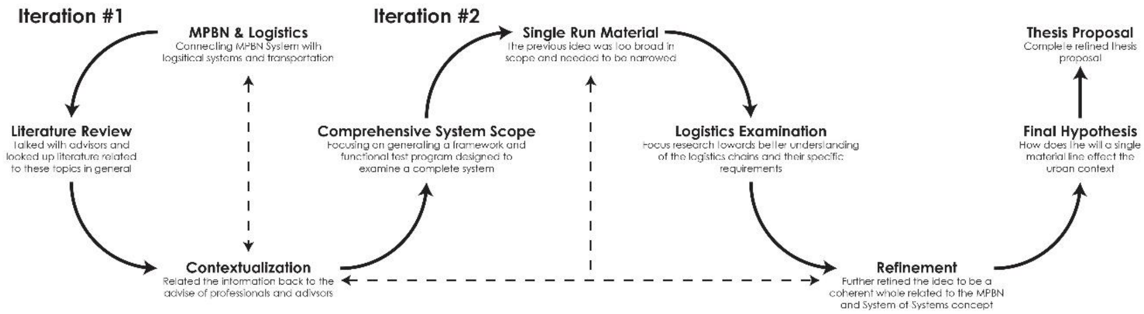

Figure 8: Hypothesis Iterative Generation

The figure above illustrates the actual outcome of this process in the formulation of the hypothesis and research question explored throughout this paper. Exploring the relation of the MPBN system in concert with logistical analysis relies on Rhino Grasshopper on a parametric model of a Shanghai, China case study in connection with ArcGIS logistical model to explore the energy and urban decision-making process when exploring a building chain from materials to neighborhoods.

2.3 Literature Review and Question Refinement

The literature review forms the primary source of theoretical and analytical information used throughout the research process in the construction of models and acquisition of calculations. Over the course of the research project, a total of three main categories were examined along with several breakdowns within each section as shown in the figure below.

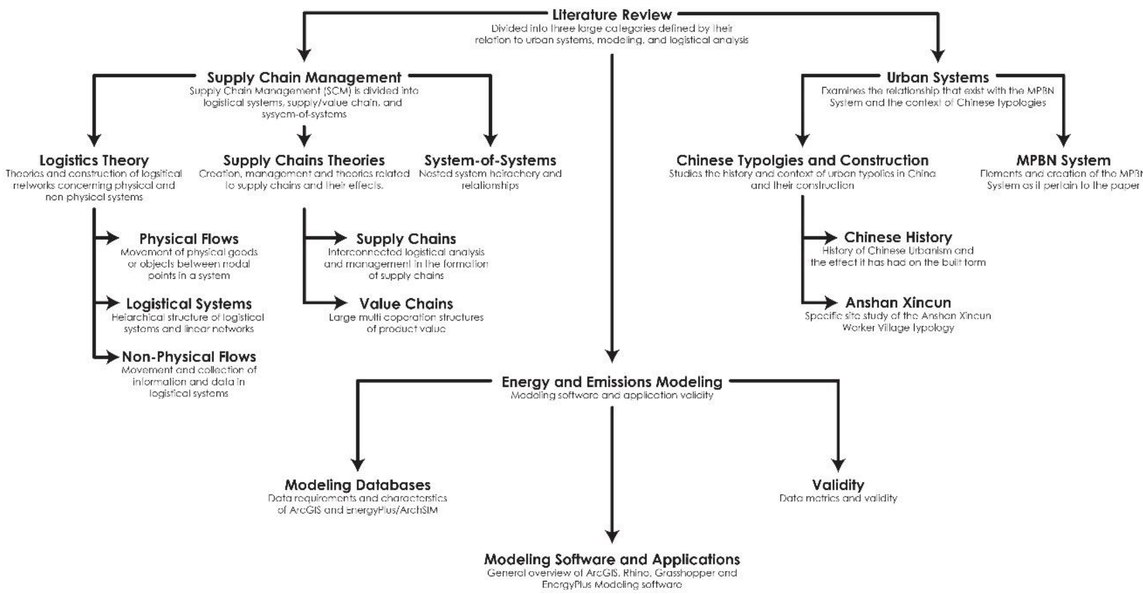

Figure 9: Literature Review

Modeling and analytical analysis formed one of the primary categories of the literature review in understanding the application of calculations and software integration to form a complete system of software appropriately integrated together. That each software package used; Rhino, Grasshopper, and ArcGIS required understanding each regarding its limitations and advantages when quantifying the energy consumption and costs associated with urban systems. Inherent in this examination of previous work done by other researchers using these tools for similar applications and the issues they faced. Therefore the modeling and analytical analysis section are divided into two primary subcategories the modeling software themselves and the calculations and equations used to determine the change value when employing them.

In addition to understanding the modeling software and constraints of the tools to be used an understanding of the actual logistical, supply chain and systems of systems methodology to be explored. Each of the subcategories built upon the other as from an understanding of the nature of logistics and how goods, people, and costs move from location to location helps to inform the way supply chains are created. This approach also relied on expert advice and interviews conducted with industry professions to gain insight, beyond theory, of how these systems in practice operate within the Chinese context. Based upon the logistical understanding comes the supply chain and value chain view of the people in how all the parts interconnect and create the system of systems which define themselves and create holons of the urban systems.

These urban systems are those building blocks of the MPBN system and the topological elements that construct and constitute the physical environment. Urban systems are sub-divided into building typologies, urban flows and material construction that are then used in buildings. The typological study was done to augment real-world data collection into the general construction methodology of Chinese buildings and how they differed from their United States counterparts. In much the same way that urban flows and material construction were used to construct typical buildings and layouts that could be placed as accurately inside of the model as possible.

2.4 Research Outline

In order to accomplish the goals of the thesis within the confines of the scope of the project, in addition to time constraints, a research methodology was employed that focuses on key objects and testing of modeling systems and metrics. Seven major components comprise the methodological approach: (1) Assumptions, (2) Literature Review/Refinement, (3) Testbed Selection, (4) Data Collection, (5) Model Construction, (6) Single Material Testing, and (7) Conclusions and Future Iterations. **Assumptions;** form the basis of the initial analysis and stating the assumptions and internal bias of the researcher and general assumptions inherent in the model are needed to properly evaluate and generate the central research questions. **Literature Review/Refinement;** adding to the validity and formulation (with eventual refinement) of the key research question and goals informed by key actors, professionals, and prior research. **Testbed Selection;** after examining each of the two test cases and performing an initial data collection the best-suited site will be selected. **Data Collection;** simultaneous to testbed selection is the collection and cleaning of existing data to test locations and preparing it for modeling. **Model Construction;** based on the existing literature, the specific data, and the eventual requirements of the research question BIM, GIS, and additional modeling systems were created for framework testing. **Single Material Testing;** models once correctly constructed, an individual single run test of the subsetted framework occurs. **Conclusions and Future Iterations;** finally, the results are compared to formulate the conclusions of the overall study and suggestions towards future iterations and corrections to the completed modeling system. Through the application of these seven steps, within the confined scope of the project, the research goal of developing a proof of concept and justification for future research into a system of systems-level thinking in an urban application can be achieved.

2.5 Site Selection

For case study analysis and data collection, three total sites and buildings were considered over the course of the study to act like the real world counterpart to the synthetic test case. Each of the buildings and areas offered different advantages and disadvantages, but only one was used because of time and resource constraints.

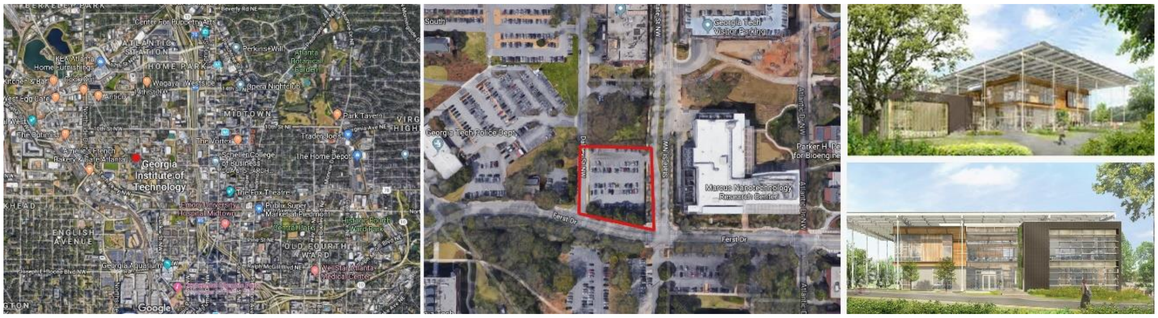

Figure 10: Test Case Option #1 - Kendeda Building

The first case considered was the new sustainable building erected on Georgia Institute of Technologies main campus. Located at 422 Ferst Drive NW it is a single large building that is being developed using the latest technology and going for a Platinum LEED rating. The main advantages of this case study were the acquisition of data and availability of working with contractors involved in the project to construct an accurate synthetic test case. However, the building posed two main challenges that ultimately disqualified it from being the primary test case for this study. The building had yet to be constructed, and it was a single building meaning application to the neighborhood scale was impossible with this building as the test case, unless a neighborhood was modeled from synthetic highly efficient buildings.

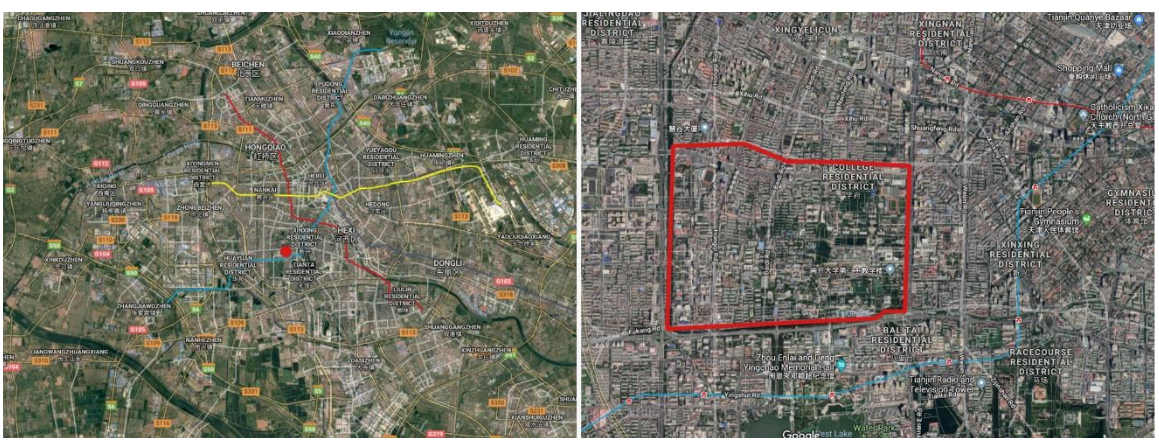

Figure 11: Test Case Option #2 - Shenzhen Campus

Georgia Institute of Technology has been considering an international campus expansion in Shenzhen in partnership with the existing university located in the city.

Tokyo was the secondary site considered for a material study given it being early in the planning process and having the study act as a force in governing design. This would have given the system being proposed by the study an ability to change urban form and material construction based upon its application. However, as with the Georgia Institute of Technology case, this posed too many challenges to be workable in the end. That like the Kendeda Building this project is not completed and proves difficult to use as a first test case. The system is still early in development to be directly applied as an urban development tool and should be used in a practical case first.

Figure 12: Test Case Option #3 - Anshan Xincun

Shanghai has several common typologies of housing and construction units, many in need of redevelopment, such as the Anshan Xincun which was a socialist style housing unit and village constructed during the 1950's. Anshan Worker village provides a real-world test that is in the processing of being redeveloped as a target housing group by the Shanghai government (Shanghai Municipal Government 2017). The same type of unit is used multiple times to construct a neighborhood as the buildings are all the same unit, or bay, repeated in two to four times horizontally and then four to six stories tall. Allowing for simple parametric modeling to be employed in a test case and simulating an entire neighborhood easy. It was for these reasons that it chosen as the primary test case for the study.

2.6 Data Collection Methods

Data collection used a total of six methods to acquire the key metrics and data used to study the effect of the urban system.

Table 1: Data Collection Methodology

Method	***Goal***	***Key Objective***
Professional Inquires	Providing validity and contextualized understanding of the mechanics of supply chain management and logistical modeling	Obtaining useful metrics and data points to aid in the construction of the logistical model
Site Visits	Observing the site, neighborhood construction and building layout to better model the existing synthetic test conditions	Generate parametric parameters to be used to simplify the construction typology of the socialist worker village typology
Literature Review	Collecting previous theories, practices, and information related to the field of study	Used to determine the current primary reasoning and theories connected to supply chains and

Table 1 (continued)

		building management in the urban context
Corporation Data	Logistical model construction and supply routing information	Used to determine the average locations, distance and facility construction involved in the logistical distribution network
Modeling Data	Building model construction and obtaining material and product characteristics	Aids in the application of materials and products into assemblies in the modeling phase of the analysis
Validity Checking	Double checking results and obtained values using verified sources and information	Adding validity to the analysis and model results through the use of accurate and scientifically rigorous datasets

From the table above the differing goals and a key objective of each tool is delineated. Through the combination of each of these discrete data collection methods, the correct method could be applied as needed and create a better understanding of the research question. Professional inquiries, site visits, literature review, corporate data, modeling data and validity checking, are used to create accurate data from sources that contribute strength to the findings of the paper. Each one employed throughout the study to aid the author in the creation of a robust research project that would allow practical application of the findings.

Professional inquiries were a necessary step in adding context and information from practitioners currently dealing with logistical flows and working in the corporate world. This step included talking to and interviewing academics, management staff and research scientists involved investigating logistical chains that influence the urban systems. The most common groups interviewed were partners of the Sino-US Ecological Urban Lab, the staff at Tongji University, the Building College at Georgia Institute of Technology, Planners at the Georgia Institute of Technology and corporate researchers connected to the Sino-US Ecological Urban Lab. Each one is providing a different perspective and insight into the framing and construction of the research model.

Despite the site being located in China and out of reach of the author, during the semesters while conducting the research, portions of the site visits conducted while the researcher was in Shanghai China between 2016 and 2017. These interviews provided the base level of insight and construction for first runs of the parametric modeling approach ultimately used. However, the site visits were not fully completed, because some were conducted before the formulation and decision to use the data as the final test case for this research. As such, additional data had to be collected and measured to determine the construction methods, materials, products and typology elements used in the construction of the typical worker village housing unit in Shanghai China.

To ameliorate this issue, local researchers and assistants were employed to get up to date data collection on the selected site location. Local Sino-US Ecological Urban Lab staff was used to get LiDAR data, measurements, material and product composition of the study area. They were asked to use a standard template that gave exact (as much as possible) measurements that were then used to create synthetic test cases. These site visits formed the primary way in which the parametric modeled buildings are constructed and developed.

A Literature Review was conducted to strengthen the knowledge and theoretical expertise of the research topics related to supply chain management, logistical modeling and filling gaps that appear in the data. This later issue exists when actual data was unavailable synthetic or created data was employed through the use of literature review sources to provide as much accuracy as possible. In addition to investigating data gaps, this tool was used to provide valid framework construction for the modeling approaches and understanding of the topic.

The most difficult source of information to obtain, but vital to the research, is the logistical and corporation dataset that is used for determining locations, average distances and the logistical routing of the network. Corporate data is often held behind nondisclosure agreements (NDAs) and trade-secrets when it comes to obtaining logistical routing and information. Further complicating this is the fact that many Chinese industries do not own their logistical routing and information systems and instead hire a third party to manage and distribute their goods. Therefore this makes the actual logistical routes complicated and not the ideal model, which is being used during this phase of the experiment, making it more difficult to obtain information and model. When corporate data cannot be obtained, general data and analysis are substituted for specific data and to allow the experiment to proceed.

Modeling data is concerned with the actual material and product statistics and characteristics that are needed to model the energy performance of buildings. In addition, this dataset contains the logistical characteristics concerned with distance traveled, type of vehicle and per unit weight and energy performance. Ideally, this data is retrieved from Chinese sources when possible, but if there are gaps or incomplete data contained in these datasets American or other accepted sources will be used. Although this will lower the specificity of the study, it will increase the accuracy and validity of the experiment as opposed to leaving gaps or holes in the data. Modeling data is used to run the model as well as construct the parametric elements of the worker villages that will be set up to run the test.

Important to all of these inquiries is the validity of the model, results, and methods that are used which is examined in detail in the final section of the information gathering stage – validity checking. Throughout the entire process methods and data will be checked against valid sources that have general data to determine whether numbers and characteristics are falling within expected values.

2.6.1 Scope of Study

The scope of the study is limited by two main factors: the number of materials to be considered and the number of buildings being modeled in the evaluation process. These limitations help to narrow the scope of the study to something that is manageable within the timeframe of the study while still providing the necessary information and test case scenario that allow a complete understanding of the framework. Only a single material supply chain is considered for the study focusing on polycarbonate/polyurethane, specifically window frames produced from this material applied to the selected building test case. All other materials and products will be held in control for this iteration to more accurately understand the amount of change experienced when adjusting one key parameter. By focusing on a single material chain, within the context of the MPBN System, the framework can be tested and later expanded upon through successive iterations that would employ this single string method multiple times. Further, by holding the rest of the materials and construction elements constant any changes in each step of the process is easier to attribute to a specific factor.

This latter scope limitation, considering a single location, is necessary for the logistical model to work for an end destination as well as supply location delivery points. By considering a single location, a synthetic model is created that mimics the real-world conditions of the selected case study in Shanghai, China. Further because all the buildings being nearly identical this is easy to scale up to the neighborhood scale through parametric repetition of the same building, with minor modifications as needed. By controlling the scope of materials considered and the total number of locations a more abstract, but practical, model for logistical and energy modeling can be constructed and tested.

2.7 Assessment Measures

Assessment and metric evaluation for this paper are divided into three general categories: energy flows, costs, and emissions which are then compared to the baseline building and one using the system detailed by this experiment. Each of these three categories constituted of multiple parts that will be used to compare the results and give quantifiable attributes to the test.

The energy flow assessment measures are divided into two separate areas of the logistical section and the material, product and building section. The former relies on taking the total number of kilometers, accounting for weight (when available), traveled in the logistical delivery of goods and applies a standard fuel consumption rate for Chinese vehicles. These synthetic routes will be calculated based upon GIS data and MOVES models that allow a reasonable approximation of the actual logistical energy consumed in the transportation of goods. These values are then multiplied by the fuel type and efficiency to produce the amount of energy consumed in the logistical portion of the experiment which can be given in energy per unit and total energy consumed.

In addition to logistical energy flows the physical flows of energy in the creation and installation of materials to final buildings will be calculated using energy modeling software ArchSIM. A parametric modeled building will be used and have a baseline structure of existing materials to be compared against the new set of materials. From this modeling, a total amount of energy can be calculated to heat, cool and maintain the building. In addition to the total amount of consumed energy for the use and construction of this material chain, the Energy Use Intensity (EUI) of the building will also be calculated to provide energy per volume for the entire building. By holding all but the test material in control, the EUI should reflect the amount of change by employing this material and this chain when compared to the baseline.

Cost is a catch-all term for the physical and monetary cost of the entire process not accounted for in the more discrete metrics of energy and emissions. The costs of the system are determined by examining the amount of money that the entire product chain costs to implement from beginning to end concerning the amount of energy consumed, time used to install and the lifetime of its use. These core metrics provide a rough Life Cycle Assessment (LCA) cost to the study and the materials in question. Additional costs that may be looked at are the total number of labor-hours required for its production and the shipping and logistical costs that are in addition to the base fuel usage and consumption.

Emissions modeling and assessment will be based upon the energy flow modeling and use the numbers provided by the analysis to examine the quantity of emissions produced at each stage, along with the percentage of the total emissions produced. To calculate these numbers the base energy flow values, for logistical and physical, will be multiplied by the energy production capability of the regions in question to determine the type and amount of emissions created. For example, in Shanghai, the power production makeup of the city will be applied to the energy consumption of the building based on the amount of coal, renewable or alternative power production method used in that region. Likewise, the fuel type will be applied to the logistical component dependent on the type of truck and fuel available and used. These two metrics will then be combined to give the total emissions of the entire system.

Important to certain steps of the analysis process, mainly the energy flow and construction costs, a baseline case is constructed and tested to provide a control for the experiment, upon which changes and deviations are noted. Thus, a baseline model will be constructed and used to assess the amount of energy produced in excess or not as observed in the synthetic test case. These will provide ratios that have meaning within the context of the experiment but have limited applicability, regarding actual energy consumption, in different cases.

2.8 Data Analysis and Testing Methods

Data analysis and testing rely on three approaches: logistical modeling, parametric baseline and material component testing which employ a set of databases that have the necessary information contained within them. These modeling approaches and data structures are constructed based upon the approach outlined in the figure below (Figure 13).

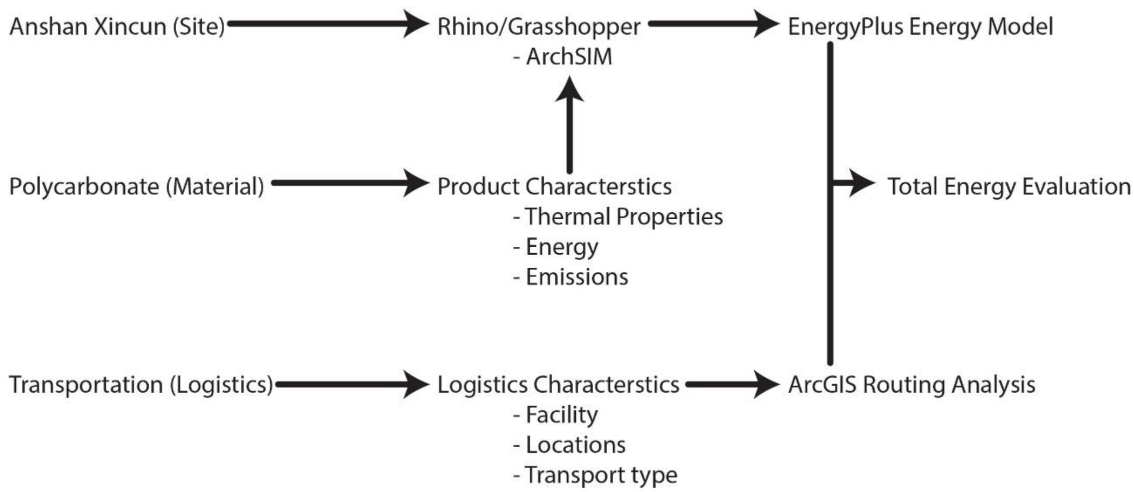

Figure 13: Overall Research Data Structure

Although certain aspects of the dataset are shared between the logistical and building modeling systems, the tests can and are run independently of each other. Logistical analysis (Figure 14) relies on the use of ArcGIS to generate distances and accurate network modeling of the routes examined in this study. The dataset contains the approximate location of facilities that are used in the actual material chain and then simulates trips from the material factory to the final building construction site. Included with the locations and distance traveled the dataset houses the average time and the type of truck, with its fuel composition, that is being used to move goods from the beginning of the cycle (material) to its end (neighborhood).

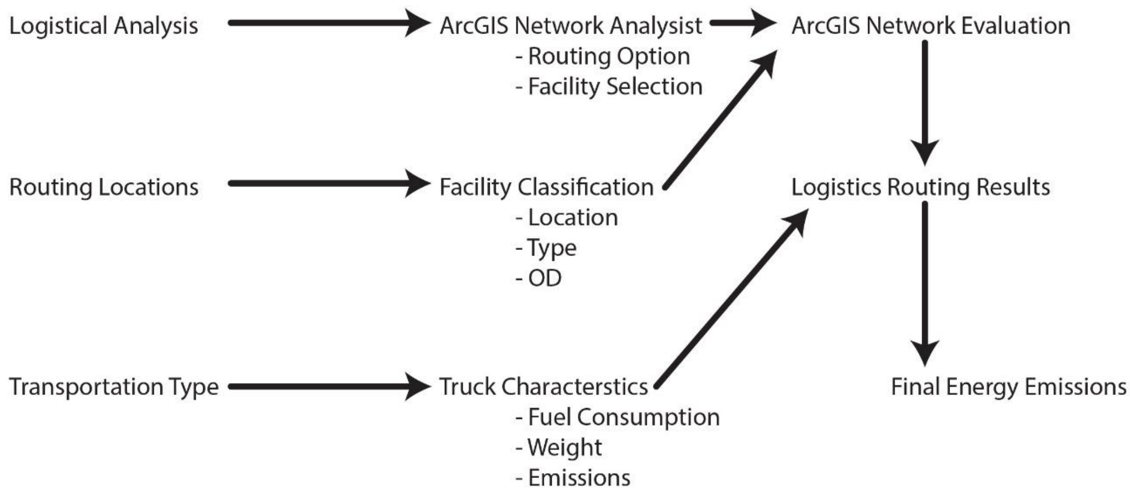

Figure 14: Logistic Research Data Structure

The building modeling (Figure 15) route relies on the use of Rhino, Grasshopper, and ArchSIM to test out a parametric synthetic building under the base and test conditions that permit material application. To create an accurate synthetic representation of real-world buildings the common elements were simplified and used to create a parametric model of the actual building, that are to be read by ArchSIM in Rhino Grasshopper to study energy performance. Five typical assemblies are modeled along with the physical rooms and openings are applied. The database structure is arranged such that the model is constructed from its component parts (rooms, roof, and windows) that are zones in which material and product properties and assigned.

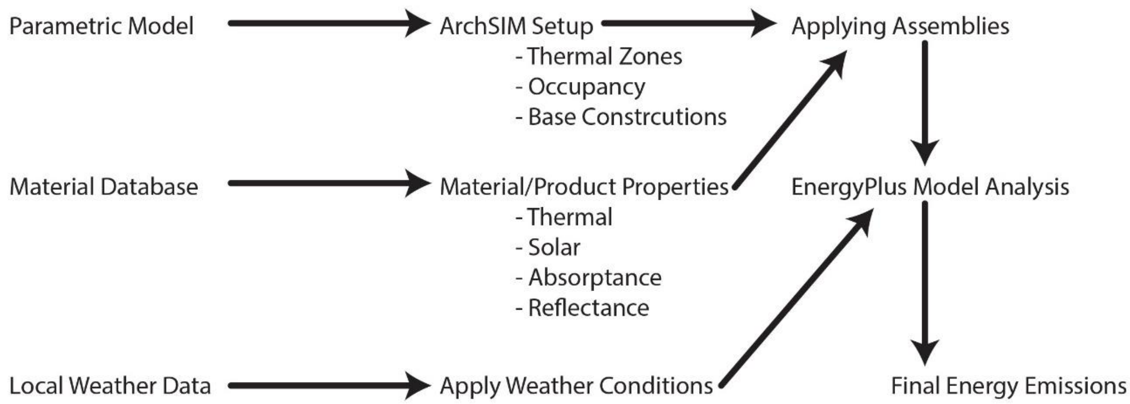

Figure 15: Building Energy Modeling Data Structure

Data testing is conducted in this two-step model of the MPBN System and the Logistical system as independent but connected, an analysis that will combine at the end to give the final value of the material and products throughout the urban cycle. This value will then be able to be ascribed and compared to similar products and materials in the same context or others by applying this same process to other locations and materials.

2.9 Research Limitations

The scope of the project, as well as the nature of research question, limit the research in terms of findings as well as hindering some aspects of the research itself. These can be divided up into two main categories of limitations and problems that were run into over the course of the research; technical and theoretical. Technical limitations where data was difficult to obtain, site visits impractical to do from the United States of America or other physical barriers experienced over the course of the research project. The largest of these challenges were related to obtaining accurate material data from material and product suppliers, location data related to parametric model construction and logistical data that is often closely guarded and difficult to get a hold of. Theoretical limitations are those caused by the construction and execution of the study and the question itself. These limitations are closely aligned with the limited scope of the project in that only one material was considered throughout the entire process, a single test location was considered, and only a single run of the system was used at this stage. Technical limitations of the project were the limited accessibility to specific logistical and shipping datasets from actual companies, the use of synthetic test cases to simulate the actual conditions, material selection focused on a single run of the entire system and the inability to perform site visits personally. The theoretical limitations of this study were the lack of multiple iteration testing of model parameters, investigating multiple materials simultaneously and the reliance on existing software that have potential issues when attempting to integrate them together.

Chapter 3: Literature Review

Three key topics form the core of the literature review and create the overarching sections of the background investigation: Supply Chain Management, their accompanying logistics systems; Urban Systems, that comprise the typologies of the study area and the MPBN System; and Energy and Emissions Modeling, using and combining existing software. Each of these core sections were subdivided into specializations concerned with specific areas of interest to the study of logistics and building modeling integration and simulation. As the primary focus of the literature review was to understand the workings and construction of logistical networks in general and to the specific area and business associated in China and situated around Shanghai. Determining construction redevelopment plans and urban flows of China and historic structures in need of renovations. Finally validating and confirming model integration and database construction for energy simulation connecting the built environment with the logistical chains that support and construct it.

Supply chain management (SCM) literary investigation focuses on the major factors impacting the urban context within the constraints of logistical networks and system of systems thinking. Built upon the understanding of SCM systems comes their connection to the contemporary, and historic systems, of urban systems as they relate to the specific study area and the flow of materials. Finally model validity and construction in the application of energy and logistical evaluation software is conducted in connection with material and logistics databases.

3.1 Supply Chain Management

Supply chain management systems and logistical analysis form the core of the logistical model that combines with system of systems thinking that facilitated the study of their union with urban systems. Each of these core elements represent different levels of the movement and management systems that exist and influence the urban fabric and those entities that exist within in it. Going up from the simplest and highest discrete resolution of logistical analysis to the most complex ideal setting of system of systems thinking.

3.1.1 3.01.01: Logistics

Logistics has long been the study of corporations, suppliers, transportation industry, academics and business professionals to explain and coordinate complex systems involving people, supplies, facilities and commercial activity. Applications of logistical management have been traced back to World War I and even prior as a means of managing the movement of troops, goods and products that are moved in large quantities. As resources and goods involved, having increasingly non-physical natures to them (information and data), the definition and complexity of these systems began to expand and deal with both the physical flow of good and the nonphysical flows of information (Iyer, A. V., et al. 2009).

The basic principles of logistics, when contending with products, can be divided into four important phases: ordering, inventory, transportation, and network design. Ordering represents the instance when a customer, or another facility, request the services or goods provided by the source corporation. Creating a point need that now has to be met with an attached quantity and quality of the good. Inventory examines the existing catalogue and storage of the corporation to determine whether the good has already been produced and is ready to be shipped, or if it has to be created. Once created, or already available, the good can be moved and transported from the storage facility to its final destination. Finally the network and distribution chain requires maintenance, or construction in the case of a new product, and sets up the structure and flow of goods and information into and within the logistics chain. Bowersox, Closs and Cooper explain the basics of this relationship in their book *Supply Chain Logistics Management* (Bowersox, D. J., et al. 2007).

In practical simulations and representation of logistics systems the use of nodal distribution networks is often employed to note facility locations, distances and the most efficient transportation points between these facilities. In their simpliest form they will appear as a series of nodes arranged spatially with weighted connections associated with costs (time, monetary, emissions, or distance) and an algorithm sorting through the most optimal arrangement of paths to meet the designated condition. Often these models have certain constraints or limitations to simulate real world condition, for example that postal trucks must always make left turns to reduce time and complex actions in road systems. Thus, evaluations of systems using logistics, in relation to supply chain management, tend to be simpler and concerned with a more rigid design scope. As a result authors such as Martin Christopher often define logistics as single line evaluation and framework for product and good distribution across businesses. It is the study of how one object directly transforms to the next with little exterior factor consideration in a tightly defined system with a direct object to maximize or minimize (Christopher, M. 2011).

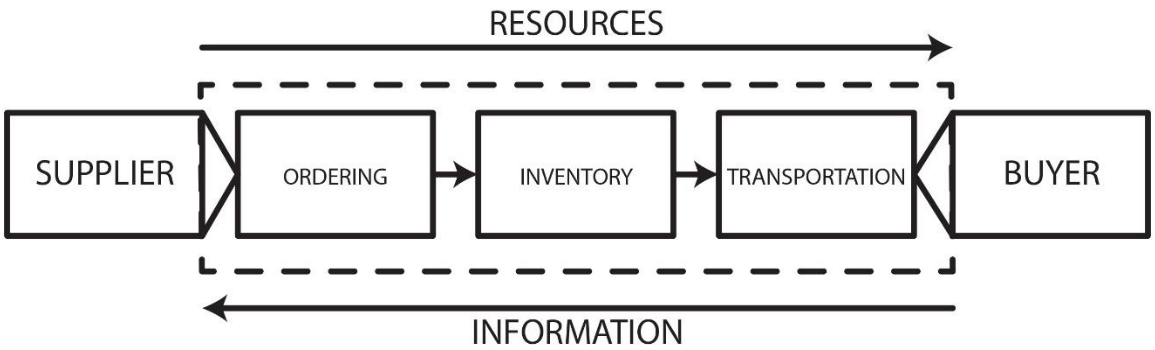

Figure 16: Linear Logistical Routing

A basic logistical informational flow chain can be observed as a linear series of events that move good forward and shift information back to creator. With the elements contained within the dashed section representing the concerns of the logistical system (Christopher, M. 2011).

3.1.2 Supply Chains

Supply Chains and Supply Chain Management are not interchangeable terms in relation to logistics and deal with the more subtle and complex nature present in the combination of logistical systems that produce a series of goods across multiple individual chains. The systems investigated by SCM tend to go across corporation boundaries and involve agencies and companies that are further up stream, or downstream, of themselves in the creation of a final product (Christopher, M. 2011) (Iyer, A. V., et al. 2009). Iyer, Vasher and Seshadri wrote about the complexities and interconnected nature of these supply chain systems in their book on Toyota's own system *Toyota Supply Chain Management: A Strategic Approach to Toyota's Renowned System*. They discuss the importance of interconnectedness that is no longer about cooperation or collaboration, but akin more to symbiosis that is mutually beneficial and interweaves the operations of one business into the other. No longer is it a linear system of good moving forwards as information travel backwards, but a networked system that loops back and iterates with goods and information in both direction across corporation boundaries (Iyer, A. V., et al. 2009).

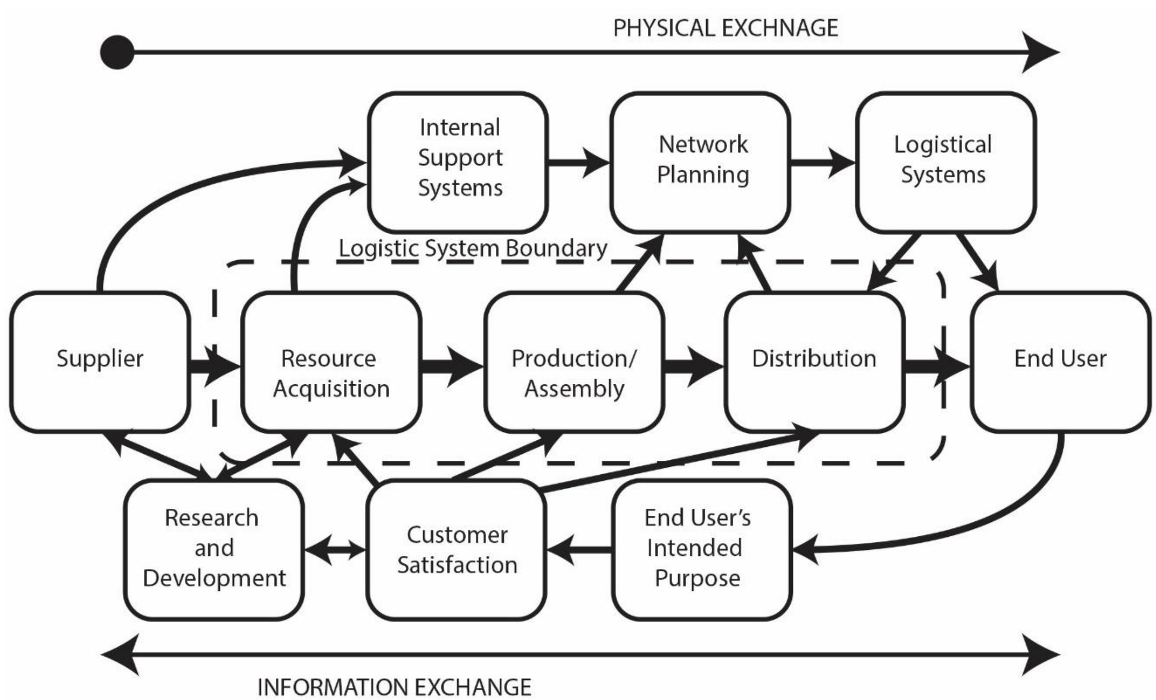

Figure 17: Supply Chain Management Systems

A graphical representation of this concept can be seen in Figure 17 that places emphasize on all parties involved in a looped system. Where Support and Primary activities work together to form the backbone of an individual business and those other departments it interacts with. In contrast to logistical models SCM includes support and human activities as elements in its evaluation of a system.

A supply chain itself, similar to logistical analysis, can be subdivided into several smaller sections: plan, develop (source), make, deliver and return. Plan contends with the strategic development of the network and logistical elements to create a profitable supply chain that effectively addresses the primary creation and delivery of the goods being considered.

Develop or source material is the process by which a strong relationship is created with the resource suppliers and the requirements needed to construct the final good. Make managing the creation of the actual resource from testing, legal work and physical construction. Delivery examines the logistical work important in moving the good from the base facility to its final point of sale. Return is for maintaining customer relations and fixing issues with goods as they arise (Association of Modern Technologies Professionals 2018).

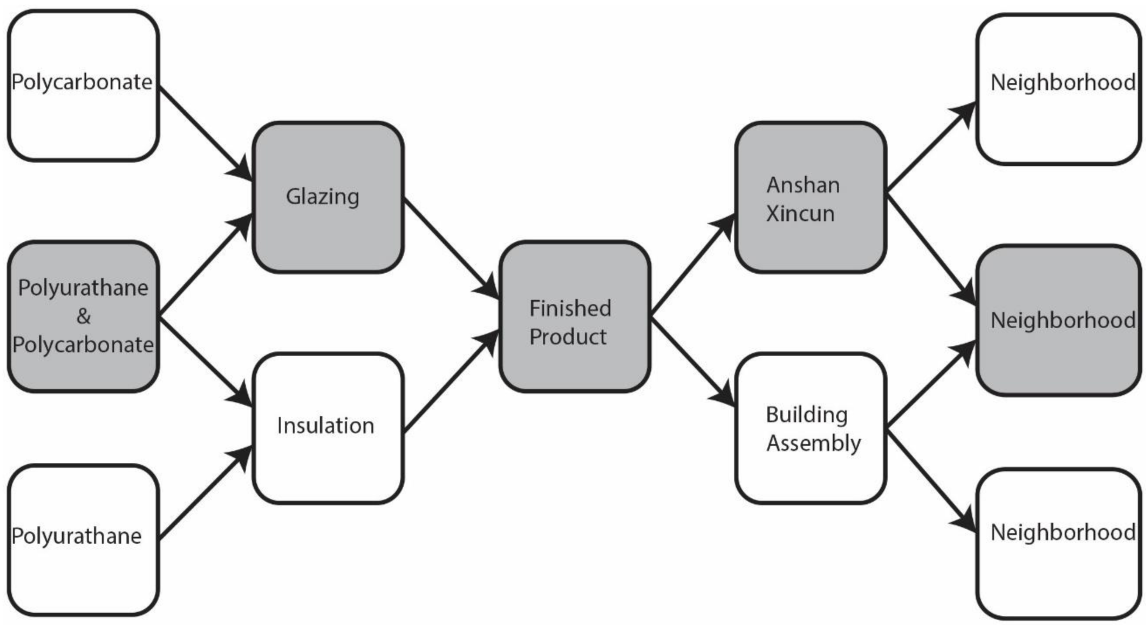

Figure 18: Supply Chain Systems

One tier above supply chain management is value chain mapping and management logistics which examines systems that are combined together in the production of materials, products or resources. This would include system evaluations of resource extraction, to refinement, material production and product fabrication and how businesses and corporation interface and interact in the system. Although certain elements of value chain analysis will be used over the course of this analysis, the focus remains on supply chain management and logistics (Wieland, A., & Wallenburg, C. M. 2011).

3.1.3 System of Systems

System of systems are complex by nature and have multiple types of organization structures depending on the type of system that is being examined. There are monolithic system structures that are comprised of *"a set of different elements so connected or related so as to perform a unique function not performable by the elements alone"* (Rechtin, 1991). Monolithic systems although can be comprised of single instances are interconnected together so tightly that the removal of one element from the system would cause the failure or fundamental alteration of the system. Simple logistical networks or one point linkage in the MPBN system bear some similarity to monolithic systems in set material and product relationships (after a contract has been defined). Where as authors DeLaurentis and Callaway (2004) state that a system of systems (SoS) is *"the combination of a set of different systems [that] forms a larger system of systems that performs a function not performable by a single system alone"* (DeLaurentis, D. & Callaway, R. K. 2004). These more dynamic systems present in SoS mirror the elements of the MPBN System as a complete entity that has multiple interchangeable components in real world applications. Business partners are not forever bound into contractual relationships and can change for cost (monetary or environmental) or individual preference driven by the stochastic interaction of human beings within the MPBN System. Hence Maier's, one of the original proposers of SoS thinking and development, owns definition which stated that they are *"an assemblage of components which individually may be regarded as systems, and which possess two additional properties: operational independence of components…and managerial independence of the components"* (Maier, 1998) is applicable to this analysis.

Apply SoS level thinking to large scale (geographic) logistics networks were an original application that Maier envisioned as a reasonable and practical application of the proposed management and conceptual framework (Maier, 1998). Since its inception SoS has been applied several times to the urban context and the systems involved in its management. To this effect Faust, Abraham and DeLaurentis in 2013 applied SoS to the management and stakeholder analysis in water systems. That although water management may appear at once to be a monolithic system, due to its complexity and high level of interactions and dependencies on exterior systems SoS proves to be an appropriate application to the study of urban systems (Faust, K. et al. 2013). Beyond the work conducted by Maier, DeLaurentis and their colleagues Ali Mostafavi (in their dissertation at Purdue University) examined the application of SoS as it pertains to infrastructure and policy innovations. Mostafavi found that through the application of SoS thinking complex and dynamic systems contesting with human behavior and urban systems, especially logistical elements, these systems became easier to simulate and predict, making them a prime candidate for their application (Mostafavi, A., et al., 2011).

Based upon the previous work done by experts and researchers in the field of system of systems and their intersection with the urban planning and urban systems, SoS are an excellent candidate for studying stochastic and complex systems. It is for this purpose that it is combined with the logistical analysis and the integration of MPBN System with the larger context.

3.2 Urban Systems

Modern urban planning, its understanding of urban systems and the role technology has and can have on the urban fabric is a relatively new codified field within the United States and abroad. Arising in the early 20th century the field diverged from other professions concerning civil engineering, landscape architecture and general architecture practices among other politically sensitive professions. In this regard planning of cities of flows of systems are not entirely new concept and have been around since antiquity in one form or another in most long lasting nations, but didn't bare the same impact as it does today (Smith, M. E. 2007). What is new, and of primary concern for this paper, is the important that technology and ever increasing levels of interconnected decisions that occur on personal and urban scales that effect greater numbers of people. As such changes in cities mirrors the rapid acceleration of technology and its effects become increasingly compounded upon existing systems as well as constructing new ones. These new and old combinations result in an ever more complex urban system that for a long time been subdivided and studied as independent in isolation from each other. In this regard technology has aided in the alleviation of historic issues that plagued cities, while lifting other restriction that had inhibited the global nature of cities that are now enjoyed.

This section explores the relationship that these historic factors have on the form and construction of buildings and their effect on modern understandings, specifically in the relation to the Chinese context. Exploring the evolution of the modern building typologies and morphologies that are constructed in Shanghai from the early 20th century to today and where Anshan Xincun falls into this spectrum. Beyond grasping the specific nature of the Chinese study case and its context is the exploration and creation of the MPBN System that seeks to explain the urban material system as it relates to the built environment. As constructed by the Sino-US Eco Urban Lab as a means of better connecting individual components of what has historically been isolated simulations and evaluations (Yang, P. P., et al., 2017).

3.2.1 Chinese Typologies and Construction

Chinese built urban form, within the context of Shanghai, can be loosely divided into four key phases of development: Pre-Colonial, Colonial, Communist Planning and Contemporary Planning. The longest period whose influences are still present in modern development and organization of space is that of the Pre-Colonial period. This phase of urbanization and building creation introduced many of the cultural traditions in urban construction and block layouts that exist to this day in spatial organization in accordance with the sun, mountains and weather patterns (Steinhardt, N. S. 1999). This is most notably seen in the Anshan Xincun site, and other locations in china, with the arrangement of buildings to have no living space with only a north facing window. Renee Chow in her 2015 book *Changing Chinese Cities: The Potential of Field Urbanism* discusses the role these historical traditions have on existing cities and the false choice that is sometimes offered in the face of historic weight (Chow, R. Y. 2015). These historical influences are not the primary focus of this study, but serve to provide context upon which later forms were created.

Following the forceful arrival of European powers in the region and after the disastrous of both opium wars the second phase of Chinese urbanization occurred as concessions were given away. That although the country attempted to practice containment, in relation to colonial influences, their effects on the nation were noticeable and profound, sending China into the Colonial phase of its development (Lovell, J. 2015). Despite the attempts to mitigate foreign influences and hold to is roots the nation was beset by internal political troubles, rebellions and envy (most strongly felt by those located near the foreign enclaves) which lead to shifts in how foreigners, and by extension, their ideas were viewed. This shift in thinking can be seen in the alteration of urban forms, map making and the way that urban space is conceptualized and ultimately organized. A divide most clearly observed by contrast of those cities part of the enclaves, like Shanghai, and those attempting to maintain traditional means of ideas, Beijing for example. In those areas like Shanghai a new style of planning was being practiced that fell more in line with Western ideology and planning motifs (Lovell, J. 2015). his period of aggressive colonial expansion, a feeling of losing one's culture, and the effects of World War II ultimately are major influential factors in what led to the rise of the People's Republic of China (PRC) and the third phase of urbanization.

Anshan Xincun was constructed during the third phase of the urban development in China following the ideology of its time and how the city was viewed, a means of production – not living. The People's Republic of China during the late 1940's to 1970's followed an urban development pattern similar to that of the Union of Soviet Socialist Republics (USSR or the Soviet Union) due to the aid and lending of Russian officers and architects to China. This began the rational and industrial shifts of the cities to match the Russian model, that cities were seen solely as a means of production and not of living and consuming as that was the tool of capitalism and the main Western Powers, predominantly the United States of America (Ma, L. J. 2002). During this period the advent of the worker village typology came about as a means of creating a housing stock that could be readily built to house as many people as possible close to centers of production. This resulted in the transformation of the Lilong large historic block structure into the macro super block of 400m x 400m or larger (Sha, Y. et al., 2014) (History of Industries in Shanghai 2015). This building typology typified the equality measures that the government saw fit to enforce on its public as a means of providing all citizens the same style and quality of housing. Focusing less on the individualization of property or public uses and more on centralized zones where one could live their entire life.

The fourth and current phase of urban form in China occurred with the political shift in late 1980's and the 1990's with the rise of Deng Xiaoping and the opening of the nation to the Western world again, along with the adoption of certain capitalist ideals. By opening the ability to rent property for a period of 70 years it opened the land market to new investment and speculation which facilitated the privatization (with aid from the government) the residential market. Individuals seeking to maximize profit, and contend with the housing issue in most urban areas, created the contemporary housing form that synthesized the socialist worker village ideals with modern construction (Ma, L. J. 2002). Though the form and layout has changed the basic function remained the same; building as quickly as possible to house as many people as possible, regardless of the form. Producing large super block clusters that are repeats of the same base building repeated as often as possible.

Within the scope of this study and the city of Shanghai three major built structures were erected over the 20th – 21st century throughout the second to fourth phases of Chinese development. Sha, et al, determined three major housing typologies Lilong Housing, Shanghai's historic housing and block construction; Worker Village Housing, often named Xincuns and the commonly erected worker housing during the 1940's to 1990's; and contemporary housing units mirrored after the west and the tower in the park style from 1990's till present (Sha, Y. et al., 2014) (Quan, S. J., et al., 2016). Anshan Xincun falls into the category of the socialist worker village housing which is categorized by mass manufactured buildings meant to house workers of nearby factories and were produced as quickly as possible. As a result many of these places, regardless of location in China, follow the same floor plan, layout, density, block structure and construction of each other. This type of structure generally is made out of concrete, has little insulation and poor energy performance. Which is why in Shanghai's 2035 plan they endeavor to fix and focus on infill development and revitalization centered on these types of structures (Shanghai Municipal Government 2017).

Shanghai's built inventory of the three most recent building typologies: Lilong (1920 – 1940), Worker Village (1940 – 1990) and Contemporary Residential Buildings (1990 – Present) comprising of over 666,000,000m^2 of total developed area, most in need of some renovation. 66,000,000m^2 of the total square meters is constructed out of older typologies of the Lilong (6,000,000m^2) and Worker Village (60,000,000 m^2) which are most in need of renovation. Worker Villages pose the easiest application for first round renovation due to their homogenous construction and character no matter location (Sha, Y. et al., 2014) (Quan, S. J., et al., 2016). It is for this reason that the central focus of this paper is combined with the Shanghai 2035 redevelopment plan and the Shanghai Worker Village (Xincun) typology.

3.2.2 MPBN Systems

The MPBN System or Material, Product, Building and Neighborhood System is based upon three complementary ideas of System of Systems, Holarchy and Industrial Ecology. The basic concept is constructed around the ideals set forth by both System-of-System's thinking as expressed by Thomas Graedel and how this interacts with the idea and philosophical construct of Holons (Graedel, T. E., & Allenby, B. R. 2002). These conceptualizations of system operations are based upon the premise that each element in the system can be constructed as an independent system, but has a dependent connection to all other aspects of the system. Shanin and Arthur Koestler work written originally in 1972, but reprinted in 2001, describes the relationship as a Janus face that has an effect on those systems that predate it in the hierarchical chain and has a direct relation going to the next system upwards of it (Koestler, A. 2001). This fundamental principle of system independence and linkage offers a better understanding of complex systems that are at work in modern urban fabrics that each layer of the system is composed of another whole system, and so on all the way down, like a Matryoshka Doll (Russian Nesting Doll). Where “a holon is something that is simultaneously a whole and a part” (Koestler, A. 2016) which is a simplification of the concepts that holds true for System-of-Systems thinking.

From this the MPBN System can begin to take form as each instance of the system: Material, Product, Building and Neighborhoods are tested and evaluated as individual whole systems, but together are parts of a large urban system that is constantly in motion. A relationship that hasn’t gone unnoticed by Industrial Ecologist Thomas Graedel in his book *Industrial Ecology* which examines the relationship of Resources, Materials and Products in the supply chain and creation of finished goods (Graedel, T. E., & Allenby, B. R. 2002). Previously each element or connection, from Resource to Material or Material to Product, were considered in isolation to each other in systems analysis, or as the next (or past) step in the system was a given embodied cost or requirements, Graedel examined the way one would attempt to entangle these systems together. This more complete system analysis yields more accurate results to the real world systems, but in turn tends to have a higher data requirement due to the stochastic systems at play and expanded complexity (Graedel, T. E., & Allenby, B. R. 2002).

The Sino-U.S. Eco Urban Lab expanded upon the concept of Holons and the integration exposed Graedel and industrial ecology to create a single line understanding of one, of many, holarchies that exist within the framework of the urban system. The building chain that is examined in the application of the MPBN system which is designed to link together each of the major stages of construction and implantation of urban construction is but one part of a great whole itself (Yang, P. P., et al., 2017). That there are a multitude of urban systems from Transportation, Industry, Information and Food flows that each are comprised of similar structure of components that work in concert with each other at different levels to form the complex systems of the urban fabric.

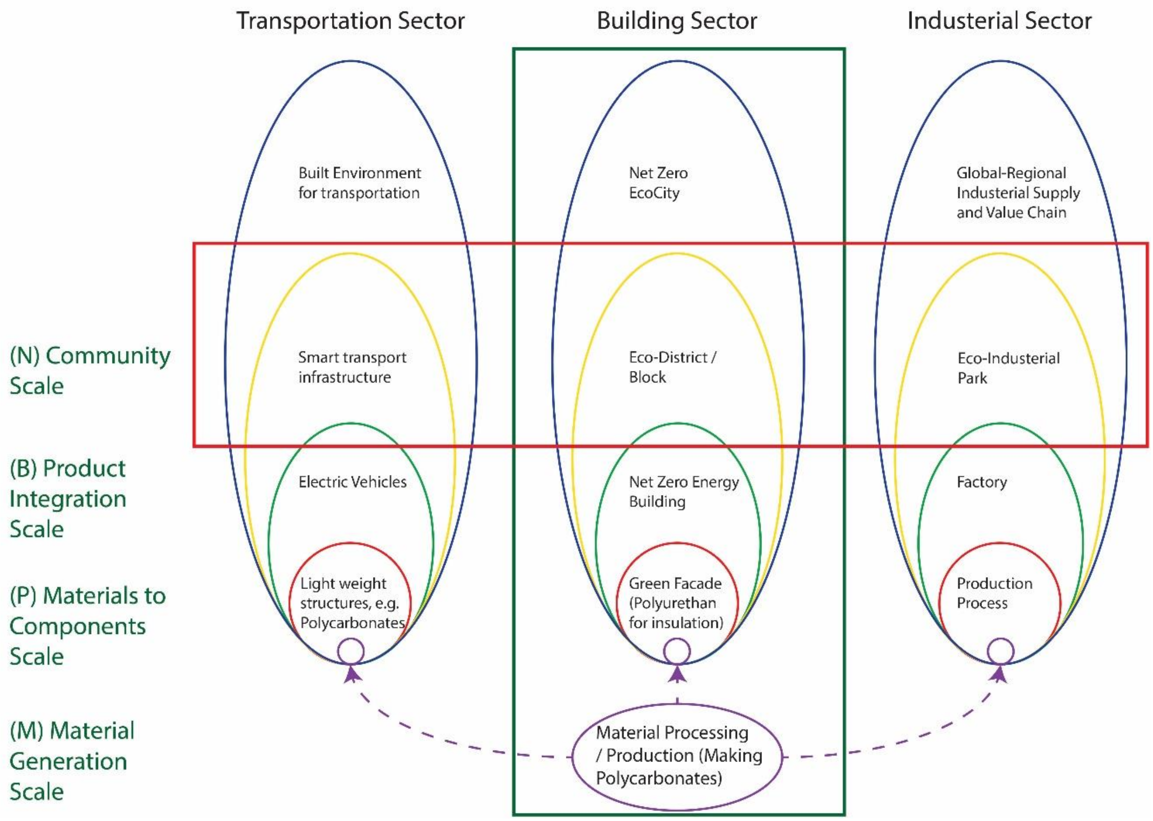

Figure 19: MPBN System Theory

As seen in Figure 19 from an *article* pertaining to the MPBN System multiple aspects combine together to form a complete future city that incorporates and contends with the simultaneous pathways active in the urban fabric (Graedel, T. E., & Allenby, B. R. 2002) (Yang, P. P., et al., 2017). The middle one, Building Systems, is the MPBN system in action and relates to the purpose of this research, stepping through the different wholes (on the left) as layers of a nested system.

3.3 Energy and Emissions Modeling

Energy and Emissions Modeling relies on three basic principles for this analysis the software employed to conduct the analysis, the modeling material and logistical database and validity measures. Modeling software explores the relevant research related to the application of EnergyPlus; ArcGIS, and its associated plugins; and Rhino and its graphical coding interface, Grasshopper and the ArchSIM plugin for building energy modeling. Modeling material and logistical database covers the sources of the data used in the actual simulation process and the need to rely on generalized data for the Chinese context. With validity measures summing up the consensus in regards to these software to act as proper energy and routing simulations.

3.3.1 Modeling Software and Applications

The primary source of material and building energy modeling, that can be used in a parametric way is through the use of DIVA's energy simulation software that acts as a plugin for Rhino's graphical coding interface: Grasshopper. ArchSIM's latest energy modeling software package is a combination of their own ArchSIM package, used historically to prepare parametric or other models in Rhino for energy analysis in the use of EnergyPlus software. However, the latest iteration of the software combine these two approaches seamlessly together such that the coding and evaluation of the energy performance of the constructed building can be tested simultaneously (ArchSIM 2018). ArchSIM, EnergyPlus and product simulations have been a standard in terms of energy building simulation that is used by the Department of Energy and LEED to certify energy calculations for prospective designs (Department of Energy 2017). Karl Rogler, in *Energy Modeling and Implementation of Complex Building Systems*, demonstrates the level of detail and refinement that can be achieved through this combination when contending with complex systems and built structures. The unique mixture of software and inputs allows for the inclusion of surrounding variables in addition to the testing of individual components in specified thermal zones of a structure. Allowing for composite modeling across a number of factors in a simultaneous model (Rogler, K. 2015).

For the purposes of logistics modeling ArcGIS has a number of benefits as a graphical information system that is capable of spatial and geographical analysis. It is able to take a number of shape files and locational data points and through code written into Network Analysis and Spatial Analysis solve P versus NP problems that deal with complex networks and determining the shortest path. Which is why the software platform has become one of the standards for the purposes of logistical and geographical analysis since its creation and popular release in 1999. Bosona and Gebresenbet have used this simulation process to study logistics supply chains related to local food networks (Bosona, T., & Gebresenbet 2013). Although of a different scale the basic principles employed in their analysis and routing analysis aid in the validity of the software application to studying and simulation logistical transportation networks. Further Sevtsuk and Mekonnen have applied the network and spatial analysis to study urban networks as it relates to gravity and spatial reach models, through the abstraction of buildings (in the case of this paper facilities) into points and mapping their reach or distance to each other along linear routes (Sevtsuk, A., & Mekonnen 2012).

3.3.2 Modeling Databases

Modeling databases and sources are split into either building simulation modeling (products and materials) and logistical routing information (locations, distances and energy costing). Building simulation modeling is based primarily on three sources of information for retrieving the proper characteristics necessary to complete the energy simulation Department of Energy, ASHREA and product websites that contain the material and product specifications for their products. The DOE and ASHREA have a long history of generalized material characteristics that have been determined through rigorous testing and observation of United States buildings (Department of Energy 2018) (ASHRAE 2015). Despite being mainly applicable to the United States the lack of regionalized data for China in the material specifications facilitated the reliance on these data sources to fill in the gaps. Further most of the general materials are indistinguishable from each other or makers location which include: specific heat, energy absorptance and the main criteria required for the purposes of building simulation. The major issue with this however is that costing in monetary amounts and embodied energy were unable to be determined as they require more specific data sources the actual construction of the concrete employed in the erection of the buildings during the 1940's to 1970's. As GRPU finished windows were used for testing purposes their exact website specification sheets were used to create the different tiers of material characteristics for testing purposes (GRPU 2013).

Logistical database modeling relied entirely on the usage of synthetic data that was created through the use of logistical generalizations, standards, corporate investigation and aid provide by professional inquiries and questionnaires. Logistical analysis of truck routing and supply chain management within China is highly controlled due to the trade secret nature and the fact that logistical networks are often owned and operated by companies outside of the product chain. This was confirmed through several interviews with staff at corporate partners of the Sino-U.S. Eco Urban Lab that had worked closely on similar projects in the past. As such average, based upon logistical standards, were used to generate the location radius of where facilities could be placed and the range of distances that could be expected in one of three models. For close and local distribution goods and services are often within 100km to 150km of their final destination, with the upper limiting being used in this case for worst case testing. This same standard often applies to centralized facilities which are located at distance from the end target of the resource, but are with that limit at a distant location. Finally the most common model that is used today by material and product assemblies that are not owned by the same corporation is a mixture of localized and centralized system which results in the greatest distance travelled (Covestro 2017) (Covestro 2018).

3.3.3 Validity

The validity of the model and evaluation metrics that were employed for testing purposes relied upon the general consensus of energy and logistical modeling and testing. Metrics to be evaluated were total energy consumption based upon the total amount of kilowatt hours consumed both annually, as determined by the EnergyPlus simulation software and by an average of the surface area Energy Use Intensity (EUI). Logistical simulation occurs based upon the determination of the total number of kilometers between all facilities in the logistics network being explored and dividing it by the total amount of diesel fuel consumed in liters. This measurement is than applied using standard conversions from MJ/L to KwH/L as determined by standard fuel energy rating for diesel fuel (Ecoscore 2018).

Chapter 4: Data Collection

Data collection occurred over three distinct phases and employed different data collection tools and parameters depending on which phase the data was collected. The first phase, the initial phase, was conducted prior and into the methodology formulation of the study. Much of this was done during the researcher's stay in China while working for the Eco Urban Lab and informed the direction that this study would take. During this first initial data collection phase mainly explored and made use of professional inquiries; site visits, and typological studies; and corporate data was gathered in conjunction with partners of the Eco Urban Lab. This first phase of data collection occurred from the beginning of June 2016 until June 2017 when the researcher left China to return to Georgia Institute of Technology.

Primary data collection occurred between August 2017, and February 2018 constituted the majority of the data used during the research. As the researcher was no longer in China data that was locked or only retrievable in China was gathered through the aid of Eco Urban Lab employees that still had easy access to the site and country-specific data. In addition, a request to corporations or other Chinese vendors were conducted using the personnel located overseas using questions prepared by the principal researcher. Research at this phase used all the methods explained the methodology section of the paper and were the most robust part of the study data collection process. Data in this stage was used to create the logistical and modeling framework used for testing in the next chapter.

Despite the large amount of data collected refined and cleaned during the primary data collection phase, not all modeling parameters and material properties could be properly constructed, especially considering the logistical modeling. Specific synthetic or generic data had to be used or constructed to complete the modeling and logistical analysis. Most notably this relied on a more specific literature review involving logistics and supply chain common metrics and material characteristics and properties used to model them in ArchSIM plugin for Rhino Grasshopper.

4.1 Initial Data Collection

Initial Data Collection occurred during the researcher's time in China as an informal process between June of 2016 and June of 2017, in which the researcher familiarized themselves with the layout, mechanics and common logistical knowledge of China. Qualitative data constituted the majority of the data collected during this phase to better understand the context of supply chain management within China. This familiarization was done while assisting the Sino-U.S. Eco Urban Lab at Tongji University while developing the MPBN System that is being tested, in part, during this research. Data was collected in one of three ways: Professional Inquiries, Site Visits, and Corporate Data.

4.1.1 Professional Inquiries

Interviews and informal talks were used to gather information on how the urban typology of Socialist Worker Villages (Xincuns) were created in China, specifically in Shanghai, as opposed to other urban residential typologies. During these conversations with Tongji Faculty and local residents (with the aid of Chinese students from Tongji University) a basic understanding of their creation was developed. They were mainly constructed during the 1950's until the 1970's and were to address the housing crisis and equality measures that were rampant and underway, respectively, at the time. As a result, the materials used during their construction were often subpar and rapidly manufactured, leading to Shanghai in recent years initiating an urban regeneration plan for the Shanghai 2035 plan (Shanghai Municipal Government 2017).

According to local testimony (mainly provided by those of the generation who were alive during their construction) explained that these were constructed quickly as possible, while still following the certain traditional elements of Chinese urban planning. Though they are still distinct from Shanghai's older urban morphology (Lilong Housing), the Xincun structures are built in repeatable bay patterns that are cramped together into new neighborhoods. Anshan Xincun itself was built close to Tongji University as part of the worker housing expansion, and although the buildings may be of lower quality, the housing prices tend to be higher (middle to upper middle income) due to their location.

4.1.2 Site visits

Several in-person site visits were conducted over the course of the year in different conditions to understand better the visual, tactile and construction differences that were present under different conditions. Located less than 750 feet (229 meters) away from the West Gate (Main Entrance) of Tongji the community is surrounded by a wall. The buildings are arranged so that every room, regardless of face or floor, has access to southern light in their main rooms. It is against Chinese tradition and development to construct a building that only has north facing windows and the Worker Village apartment structure adheres to this rule.

Figure 20: Anshan Xincun Site Photos

From these site visits, certain key characteristics and typographical elements could be identified but would only be quantified and used in a parametric model after Primary Data Collection had occurred. Each of the buildings were divided up into structure bays that contained four total residential units and backloaded hallway and corridor on the northern side of the building. These bays themselves were a mirrored floor plan that had an “L” shaped unit that had a square unit nestled inside of it. Each of the buildings was then between two and four bays in length (although there were exceptions to this) and consisted of between four and six stories. Each building had a sloped roof, white exterior walls, windows in each of the main living rooms and what appeared to be solid concrete walls and flooring for its construction. This information was used as the baseline for model construction and expansion during the more comprehensive phase of data collection.

4.1.3 Corporation Data

Interviews were also conducted with partners of the Sino-U.S. Eco Urban Lab, to understand and create the MPBN System. Over the course of the year-long study process that eventually resulted in the initial codification of the MPBN System several revelations surrounding logistical chains and routing within China, and internationally, were revealed. In essence, it broke down loosely into a three-tiered system: Material and Product Specifications, Resource Arrival and ultimately Delivery.

Material and Product Specification was the beginning of the material design process and the effective beginning of the supply chain, as materials were considered to be already mined or to have existing fixed properties. At this stage conversation with clients (product manufactures or builders) are done to determine best what exact properties and characteristics need to be imbued into the material to obtain the expected results. If this is being done with the direct architectural (urban scale) client, then the product manufacturer is also brought in to handle the synthesis of the material to the finished good. From this information, the material's resource needs can be determined, and the material can begin to take physical shape. This stage relies entirely on information exchange and keeping and has no physical exchanges present in it.

Resource Arrival and Delivery share several similarities in how they are structured and operate, although the number of steps and goods vary between the two. In both systems, a truck, or logistics vehicle, enters the system from another factory, or location, outside of the supply chain system that is directly concerned with the material examined. From there the vehicle arrives at the facility and unloads the raw, or refined, resources at the production plant and imparts embedded energy resources into the system.

In the case of Delivery, the goods are picked up from the facility, in the same manner as resource arrival, and begin to be transferred to the product production facility. However, before this is accomplished the materials are taken to a logistics center, owned by a third party, visiting additional factories along the way. At the logistics center, they are unloaded, stored for a time and then reloaded and shipped out, along with other goods, to the product production facility along with several others in route trips that are not part of the specific material to product supply chain. The exact details of this relationship are further detailed in the Primary Data Collection phase.

4.2 Primary Data Collection

Primary Data Collection constituted the majority of the data collected and ultimately used for this research over the course of 2017 and 2018 and followed the methodology outlined in Chapter 2: Methodology. This section is subdivided into six key categories of inquiry: Professional Inquiries, Remote Site Visits, Literature Review, Corporation Data, Modeling Data and Validity Checking. Each of these sections briefly describe the manner of research used to obtain key values and variables from each method. More in-depth analysis and applicability are contained in Chapter 5: Analysis and Testing or within Chapter 3: Literature Review.

4.2.1 Professional Inquiries

During the one year study, several professional interviews and questionnaires were conducted, mainly using email, to previous partners involved with work that the Sino-U.S. Eco Urban Lab was involved. These questionnaires were designed to give better insight into the logistical routing, capabilities and material properties at the fine-grain scale of the study.

Table 2: Professional Inquiry Survey

Definition of Material Component	Material components are pieces that are used to construct materials themselves. For example, a window is a material, however the glass/polycarbonate is a material component in that material. These are made by component vendors or suppliers.
Definition of Material	A material is finished product, constructed out of material components that can be installed and used as a part in the construction of a building. These include things like windows, insulation, wood studs, and other forms of finished construction materials that become one part or component in an assembly construction. These are produced and sold by material vendors or suppliers.
Definition of Assembly	An assembly is a type of construction element such as a wall, floor, roof, or the major internal and exterior construction types of the envelope and interior structure of a building. An assembly is constructed out of multiple parts.
Definition of Smart Material	Smart, in buildings materials and cities, has many different and competing definitions. For this research and collaboration, the working group defines a smart material based on these key properties: Has a lower environmental impact than other competing materials, Smaller Carbon Dioxide Footprint, lower lifecycle impact, and easier to recycle and reuse. Same or better performance characteristics than the material to be replaced. Energy Savings, Passive systems, and savings must be accrued. Equal or more appeal aesthetics or quality to competing materials increases marketability and more likely to be well received and used.
Name of Material Component to be Studied	(The study will focus on one material)
Material Component Applications, in Relation to Assemblies	(Known uses for material component in assemblies, if applicable)
Known Material Suppliers, Name of Product	• (Company Name, Product Name, Material Component Used) • (Company 2) • (etc.)
Known Material Component / Material Competitor	• (Company Name, Product Name, Material Component Used) • (Company 2) • (etc.)

Table 2 (continued)

Material Component / Material Attributes	• Weight: (kg) • Density: (kg/m3) • Thickness: (mm) • Specific Heat: (J/kgK) • Conductivity: (W/mK) • Thermal Emittance: (0-1) • Solar Absorptance: (0-1) • Visible Absorptance: (0-1)
Lifecycle Assessment Attributes	• Cost: (RMB or USD) • Material Lifespan: (Years till replacement) • Embodied Energy:
Average Distance Between Material and Product Suppliers	• Distance: (KM)
Transportation in Logistics Network	• Mode of Transit: (truck, rail, other) • Type of Vehicle: (specific truck model or rail)
Storage Type and Length	• Storage Conditions: (Exterior, interior, cooled or other) • Length of Time in Storage: (How long is it off the truck at Logistic Centers)
Additional Notes	(Additional material notes go here)

The survey was designed to be brief, but getting the key aspects needed for study, based upon real-world conditions while also defining key terms for the study. The definition of smart materials and other key variables contained at the top of the survey, come from the work that had been done previously concerning the MPBN System (Yang, P. P., et al., 2017). Beyond the key definition provided at the top of the study the body was simply concerned with key factors important to the research, allowing at the end for additional notes to be added that the respondents felt valuable.

Although several of these were sent out the majority of the information was often difficult to obtain due to the organizational structure of the corporations asked and the sensitive nature of the data itself. Because of this several of aspects were often left unfilled, mostly the first section pertaining to partnerships and the final section detailing logistical routes. Resulting in the reliance on generalized data, synthesized locations, and inference from what they were able to say regarding these topics. They often mentioned their reliance on third party's logistical companies to transport goods around from major centralized factories located in three primary locations near Shanghai, Guangzhou, and Beijing to product manufacturing sites.

4.2.2 Remote Site Visits

Due to the study site being located in China remote site visits were necessary to compile and create technical data and detailed analysis for model construction. To accomplish this, task researchers at the Sino-U.S. Eco Urban Lab were asked to visit the site on the researcher's behalf in collecting critical data. Although basic analysis of the site was conducted in the pre-study phase of 2016-2017 more nuance and physical dimensions were needed to create the parametric model used for energy analysis. For this, three key parameters were examined: the structural composition of the buildings; dimensions of the building's interior, windows and exterior; and the base level parameters used in parametric generation.

The material composition of the products used in the assemblies of the building were simple and easy enough to determine based on observation and interior views of the space. Simplified the buildings are constructed from five assemblies: Floors, Walls, Roof, Slab, and Windows. Of these five, only walls have a further subcategory depending on if they are interior or exterior walls, but these are simple in terms of building construction. All floors are constructed in the same manner of 0.305m (1ft) poured concrete flooring with tile, wood or left barren depending on the unit and nothing on the other side for the ceiling. Exterior walls are made of 0.406m (1ft – 4in) solid concrete masonry unit (CMU), or Chinese equivalent, like material that is painted on both sides and has no disenable insulation installed on it, or in it (based upon examination of destroyed or demolished buildings in the area). Interior walls are made of a similar material, but are only 0.203m (8in) in width and are not covered by any insulation either. The roof of the building were more difficult to discern their construction and material components, but from what was observed they appear to be wood construction with tiles placed on sloped roofs and lack insulation as well. All buildings are thick poured concrete slabs on grade and are similar (but thicker) than the regular floors and composed of similar materials. Two types of windows were present on the buildings large ones (size) and smaller ones (size) which both followed the same single pane, wooden frame construction with low to little insulation value. Although the exact materials, in terms of properties and characteristics, could not be determined from observation they provided the necessary guidelines for the use of general materials to be applied in their place.

Following the existing material analysis, dimensions and typical unit, bay and buildings sizes were logged to create a generalized unit of one building which would ultimately be used for modeling purposes. Each building ranged from between four to eight stories in height with each story being approximately 2.80m (9ft – 2in) in height. Every building in the Anshan site is constructed out of a simple bay measuring approximately 33.8m x 13.2m (110.9ft x 43.3ft) that can be subdivided and mirrored for the purposes of modeling.

Apartments are composed of between two to four bays put together make each building between 67.6m (221.9ft) to 135.2m (443.6ft) in length. The standard floor to ceiling height was about 2.49m (8ft – 2in) meaning with the floor thickness floor to floor height was 2.80m (9ft – 2in).

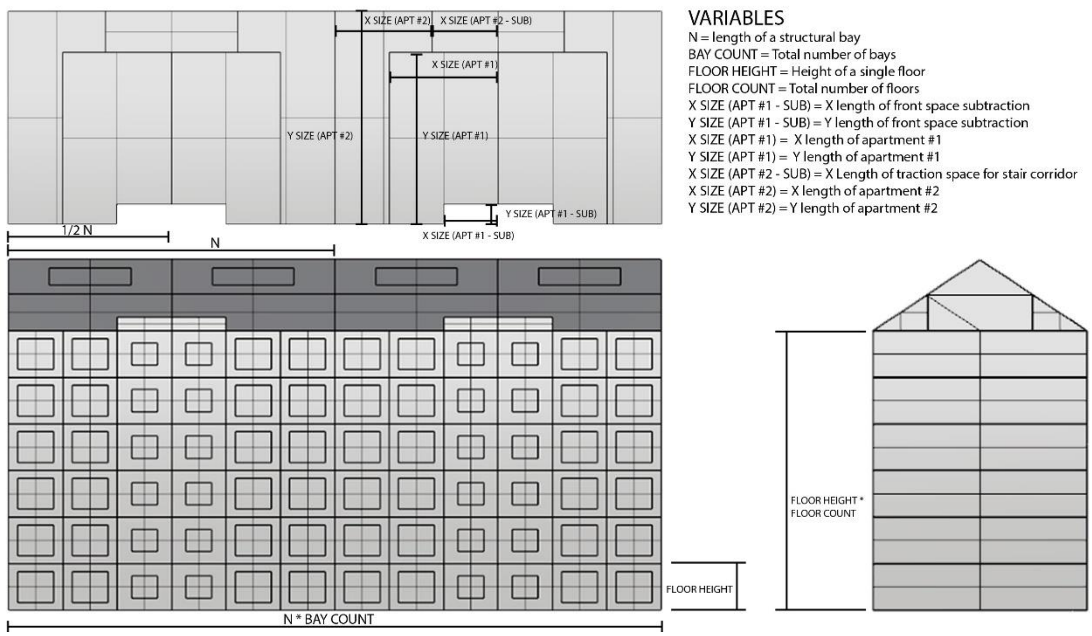

Figure 21: Parametric Model Construction of Anshan Xincun

The final part of the remote site sensing and visits was to determine the simplest means to deconstruct and reconstruct the buildings digitally. To accomplish this the building was created through breaking it down to its three base components that constituted half of a bay: an “L” shaped apartment unit, a rectangular apartment unit and the transit corridor the was located on the back (Figure 21). Further windows were modeled as a ratio proportional to their total wall coverage, instead of their actual size. From all the data collected it was then possible to construct the fully parametric buildings used in Rhino/Grasshopper and ultimately test their energy performance in Chapter 5 Section 5.01.

4.2.3 Literature Review

The literature review drew from a number of sources (white papers, books, professional recommendations and business manuals) to develop a better understanding of the logistical supply mechanisms involved in system-of-systems at the urban scale. Similar work was undertaken in developing an understanding of Chinese housing typologies and construction in Shanghai and their associated logistics network. However, a major portion of the literature review is associated with the collection of resources to properly construct the logistic network and the material component properties used in the building construction. Pertaining to their energy consumption, embodied energy and modeling them from which ASHRAE (ASHRAE 2015), DOE (Department of Energy 2018), and Individual Product Suppliers (GRPU 2013) relied on as guides for modeling purposes. More information on the exact contents and nature of the literature review is found in Chapter 3.

4.2.4 Corporation Data

Despite the essential role that corporation data has in this study as the foundation of the logistical systems, this proved to be the most challenging data set to obtain, or even synthetically construct. Several attempts were made to previous partners, material companies, contractors, product manufacturers and logistic companies both in the United States and in China, but few concrete details were supplied. Most companies were unwilling to give up, hint at, or give generalizations of the logistical routes and methods due to trade secrets and without a non-disclosure agreement were unwilling to talk at length about their procedures. This proved difficult as a large part of the complex system-of-systems logics of the system being explored is the logistical and corporate data that is required to ground and create realistic models of urban systems.

The data that could be obtained was often not dissimilar from the information gathered by the professional inquiry surveys and contained general location of the facilities. That the major locations of facilities in China, close to the area of study (Anshan Xincun Worker Village Housing in Shanghai) was located outside of the city proper. From there the goods were loaded onto a truck then transported to storage facility owned by the logistics company (referred to as a Logistics Center for the analysis). After which it would be stored for a short-time-period (a few hours to two days) and then repackaged and shipped off to the product production facility (after visiting several non-supply chain related facilities). At which point it would be transformed into a final product (that could be applied into a building assembly) and loaded up and shipped off to a wholesaler located around Shanghai proper, where it would be ordered from by the contractor. From there it would travel to the store, to be picked up by the client, or taken directly to the construction site/final destination where it would be installed into the building. This information was then used to create the logistics model, upon which synthetic data was used to fill in gaps and construct the actual distances traveled to provide the basis for the analytical study conducted.

4.2.5 Modeling Data

Modeling data fell into two major categories for this research project: logistical and building modeling data. Logistical data consisted of facility typologies, facility locations, routing information, Chinese road shapefiles, transportation type, power grids and the fuel consumption rate. Based upon the average logistical distances three major distribution networks were found to be active in the area. Localized material and product production (centralized or decentralized), distant material and product production (centralized) and distant production combined with localized production (Iyer, A. V., et al. 2009) (Covestro

2017). When combined with the information collected from the professional inquiries and corporate data these distances define a 100-150km ring outside of Shanghai and the same centered around Guangzhou, which are the sites selected for the ArcGIS logistics model. A base Chinese road shapefile was employed, and trimmed, to the surrounding area of interest and although it did not contain all minor roads the macro road network was sufficient for this level of testing (Wu, Y. 2018).

Building modeling data focused on the material characteristics, product characteristics and surrounding data constraints (weather, shade and ground) are applied to the baseline model created through the remote site visits. The primary source of material data was through the combination of site visits and ASHRAE's material database containing product and material characteristics (ASHRAE 2015). As the baseline building's materials are not possible to determine by historic investigation or site visits, beyond its basic characteristics. Different final material glazing product and material characteristics were determined based upon the use of actual product data as obtained through GRPU's website (GRPU 2013). Weather and shading data was constructed and based upon the Energy+ weather data database using Shanghai specific data (EnergyPlus 2018).

4.2.6 Validity Checking

Model, logistics, material and product validity was confirmed by comparing known material databases like ASHRAE and DOE with the observed and collected data use for test purposes. Based on these sources the material and product data were constructed then double checked, and the logistic routing confirmed. Validation also involved the use of satellite images on the part of the researcher to confirm the basic findings that were noted by the remote site visits. Through the use of Baidu and Google Maps the dimensions and general layouts of the buildings were confirmed along with their heights, based upon street views that aligned with the measurements taken by the remote site visits.

4.3 Synthetic Data Creation

Despite the extensive nature of the Initial Data Collection and Primary Data Collection phases, several gaps and holes in the data were left unfilled due to time, availability and resources available to the researcher. Some of these issues did not become apparent until testing was underway and gaps had to be filled in order to complete the study with a sufficient level of accuracy. As a result, several synthetic data sources had to be created or altered, based on existing general precedents, to best complete the study. These may have added additional errors into the calculations, of which it is hard to say how much, but without the creation and use of such data the analysis would not have been possible. This section will go over the data creation methods, actual sources and the data that was created or used for this study. In this regard three methods were used to create or develop the synthetic data: Literature Reviews, Logistical Data Construction and Modeling Data Construction.

4.3.1 Literature Review

Similar in structure to the base literature review conducted during the Primary Data Collection phase, the focus and intent of the two differed. The synthetic data creation literature review focused less on an understanding of the subject and more on exact sources to fill gaps in the data previously collected. The substitution relied heavily upon ASHRAE (ASHRAE 2015), DOE (Department of Energy 2018) and previous simulations conducted by the Eco Urban Lab (Yang, P. P., et al., 2017) to create the synthetic data necessary to run the energy simulations. Rather than the theoretical construction of models or the Shanghai context this review examined and collected material, product and facility properties. These can be readily seen in Chapter 5: Analysis and Testing under each of the two test scenarios for Logistics or MPBN System Analysis.

4.3.2 Logistical Data

Synthetic logistical data relied on the use of United States of America standards for specific applications of the trucking and logistical network that proved to be more obtuse from Chinese companies and data sources. Although routing and networking distances and locations were mostly determined by localized Chinese data sources transportation, weight and actual facility locations were synthetic. Actual facility locations are unable to be determined or had to be abstracted from data sources. As a result, facility location represents the average distance between those locations. Trucking fleet composition, fuel consumption and power grid data were generated from national averages (Transport Policy 2018). These synthetic data sources and information was required to complete the logistical analysis and in future iterations (or practical applications) of the system should be endeavored to be kept to a minimum.

4.3.3 Modeling Data

Material and product characteristics for the general construction of the baseline and construction of the parametric shading model composed the majority of the synthetic data employed for energy modeling. Baseline model assembly construction relied on the use of ASHRAE and DOE generic building materials that were the closest match to the visual observation of the site (ASHRAE 2015) (Department of Energy 2018). As a result these generic concrete materials and tiles represent not the actual performance characteristics of the actual site, but the best approximation that could be achieved with the limited resources that were available. Neighborhood modeling was based on the same building copied into a 3 x 3 square, with the central building be the test object, and spaced 10m (30ft.) apart from each other. This was based on their similar structure as observed from site visits, as well as satellite imagery, but is ultimately synthetic due to their orientation, exact layout and structure.

Chapter 5: Analysis and Testing

The analysis and testing of the effects that material tracking, choice selection, and logistical routing have from a bottom-up approach in the urban context is divided into two discrete but connected phases: MPBN System Analysis and Logistical System Analysis. These two systems were first tested independently of each other, before being combined in a final analysis based on energy use intensity (EUI) per floor area of the affected buildings. This technique was used to normalize the results and provide a means to adequately test all scenarios and compare results.

5.1 MPBN System Analysis

The MPBN System Analysis' testing objective was to determine the effect that changing material, and by extension, a product, would have on a single building's energy performance. This ideal building would then have its neighboring buildings modeled to more accurately estimate the total energy performance in a neighborhood setting. This result from a single building, with its neighbors, would then be used as a base to examine the total energy used, or saved, when converting all of Anshan Xincun to newer more energy efficient construction. To accomplish this task, a total of four test cases would be conducted relying on the same model and research design approach.

The four test cases were: Baseline, Low-Grade Smart Glazing (double pane), MidGrade Smart Glazing (double pane) and High-Grade Smart Glazing (triple pane) window systems. To conduct these experiments the parametric base model was constructed, using Rhino's

Grasshopper plugin and the ArchSIM/EnergyPlus software plugin, based upon the parameters determined during the site visits and typology information. Thermal zones, neighboring shading, and materials were applied to the simulation, creating the baseline construction. After running the initial baseline all materials and conditions (occupancy, heating and cooling and ventilation) were held constant, except for the windows glazing variable. Isolating the testing variable and any resulting changes in energy performance would then be accounted for by the changing glazing testing parameter.

5.1.1 Parametric Model Creation

All test cases, for energy modeling, are based upon the same parametric model constructed using Rhino's graphical coding interface, Grasshopper, along with the use of DIVA's ArchSIM and EnergyPkus combined plugin to conduct the final energy analysis. For this purpose, the model is subdivided into four major construction coding that is employed in the creation and testing of the ideal Anshan Xincun building: key variables, building construction, neighborhood shading construction and ArchSIM. This section will go into the basic details of the model construction, and the variables used to generate the synthetic test case.

Key variables formed the basis of the parametric modeling process and are used to control the size of the individual rooms, window sizes, bay construction, floor count and all aspects of the building that are not fixed. These variables are split amongst building construction, bay construction and Building Assemblies, and neighborhood construction into the 3 x 3 neighbor synthetic block. Bay construction relies entirely on the building construction model and controls the variables related to the size of the two living units and the transit corridor that are then mirrored to create a complete bay. Building assemblies control the total number of floors, ceiling height, number of bays and the window ratio. Window ratio was used instead of defining actual window size due to little effect occurring when accurately modeled and the just added extra complexity for little gain. Neighbor creation was used to delineate the number of buildings in the synthetic block (in large case studies it could exceed 3x3) and the distance between buildings in X (by a ratio of the bay size) and Y.

Table 3: Parametric Modeling Key Parameters

Variable Category	*Description*	*Variables*
Bay Construction	Bay construction relies on the creation of a standard rectangle that is then subdivided and subtracted from to create the final rooms and thermal zones.	• X Size (APT #1 – Sub) • Y Size (APT #1 – Sub) • X Size (APT #1) • Y Size (APT #1) • X Size (APT #2 – Sub) • Y Size (APT #2) • X Size (APT #2)
Building Assemblies	Assemblies controls how often the bay constructions are repeated, in addition to the height of the building and window sizes	• Floor Height • Floor Count • Bay Count • Large – WR • Small – WR • Roof – WR

Table 3 (continued)

Neighborhood Creation	Creates the adjacent buildings used for the ArchSIM shading model simulation	• X Distance • Y Distance • Building Count X • Building Count Y

Bay creation is entirely generated on based upon simplification and parametric model created out of the site visits. Where Y Size (APT #2) and X Size (APT #2- Sub) plus X Size (APT #2) control the general footprint of half of a bay, 10.4m x 13.9m. Each of the other variables used in the model controls the size of the two rooms, with the remaining element being the transit corridor and a subtracted volume on the front of the building.

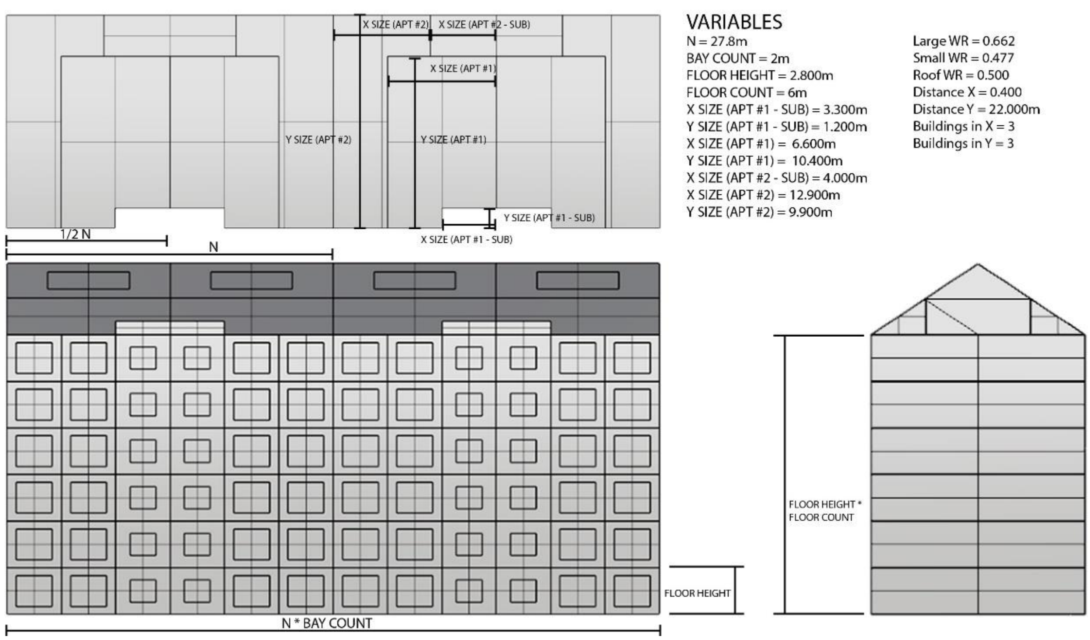

Figure 22: Parametric Variable Testing Conditions

Figure 22 shows in plan the relationship of these key variables and their application in the creation of the building. Each apartment unit is constructed through subtraction of the general rectangular half bay and further subtracting the transit corridor from the base layout as well. With Apartment #1, the rectangular unit, being the most complex, requiring four variables, to account for the subtracted mass on the front of the building.

Once created the base bay construction is then mirrored along its right edge, apartment #1, and has the building assemblies variables applied to it (Figure 22). The outer line of each unit is extruded, generating the surface that is used as the wall for energy modeling, according to the to the Floor Height variable (2.8m). The extruded bay is then merged and arrayed horizontally by the total number of bays (Bay Count), which for this study was two. Once arrayed horizontally they are grouped again in Grasshopper using the Geometry storage entities and Boundary conditions that then has a Z vector applied to them (Floor Count) of six. Finally, windows are created through segmenting the thermal zones and placing an Item, correctly justified, upon the wall and determine the size through the use of an Area and Scale operator that applies the correct Large or Small WR variable to it (0.662 and 0.477 respectively).

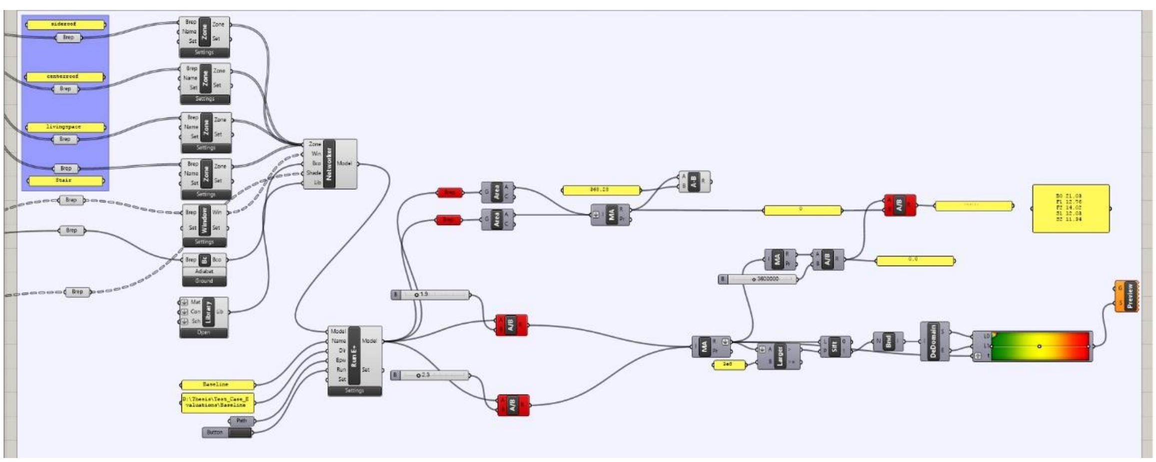

Figure 23: ArchSIM Grasshopper Modeling

With a fully modeled building (Figure 22) the adjacent buildings for shading simulation can be created, by merging all the complex geometry into a single solid object to be arrayed around the test building. Each of the buildings is placed at the origin point of a rectangle created through the combination of the existing building variables, in the X direction, and a ratio applied to it (X Distance = 0.400). Whereas Y distance is a set distance (22m total). Building count X and Y determine how many buildings are created around the central building in the array.

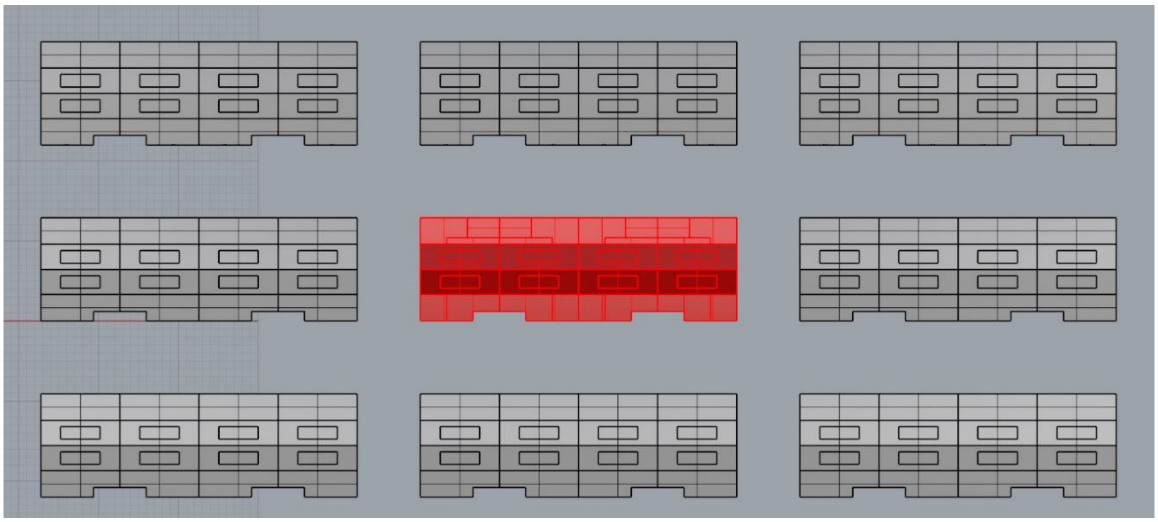

Figure 24: Shading and Neighborhood Layout

Once the building and its adjacencies have been created the ArchSIM module can be applied to the central building and material and product properties applied to it (Figure 24). For this the building is divided into four thermal zones, window construction and assembly construction. The thermal zones include the living zones (all arrayed APT #1 and APT#2), Stairs (Transit Corridor), Roof and slanted roof that each has specific materials and assembly constructions applied to them. Further, they have occupancy tables, determined for this study based upon ASHRAE stands for residences in the United States (ASHRAE 2015). Window construction and assembly construction are similar due to both creating the assembly itself out of the material database.

5.1.2 Analysis Setup and Material Database

Energy+ and ArchSIM rely on the thermal zones and assembly constructions to apply the materials and products to the proper zone and assembly with it. Each zone is separated into five assemblies: Exterior Walls, Interior Partition, Roof, Flooring and Ceiling and Ground Floors. Due to the nature of the construction in Anshan most assemblies are made of a single product or two products. Table 4 and Figure 25 contains the basic product information and an example of the characteristics required to construct the model.

Table 4: Material and Product Testing Properties

Category	*Material/ Product*	*Thermal Zone*	*Type*	*Assembly*	*Thickness (mm)*
Opaque	Cement Screed	Surface	Screed	Flooring	65
	Lightweight Concrete	Surface	Concrete	Flooring	304.8
	Roofing Tile	Surface	Roofing	Roofing	3.175
	General Concrete	Surface	Concrete	Walls	406 or 203
	Tile	Surface	Flooring	Flooring	3.175
	Gypsum Board	Surface	Other	Walls	15.24
Transparent	Clear Glazing	Window	Glazing	N/A	6
	Clear 6mm	Window	Glazing	N/A	6
	LoE Clear 6mm	Window	Glazing	N/A	6
	Xenon	Window	Gas	High Grade	6
	Krypton	Window	Gas	Mid Grade	6
	Argon Gas	Window	Gas	Low Grade	6

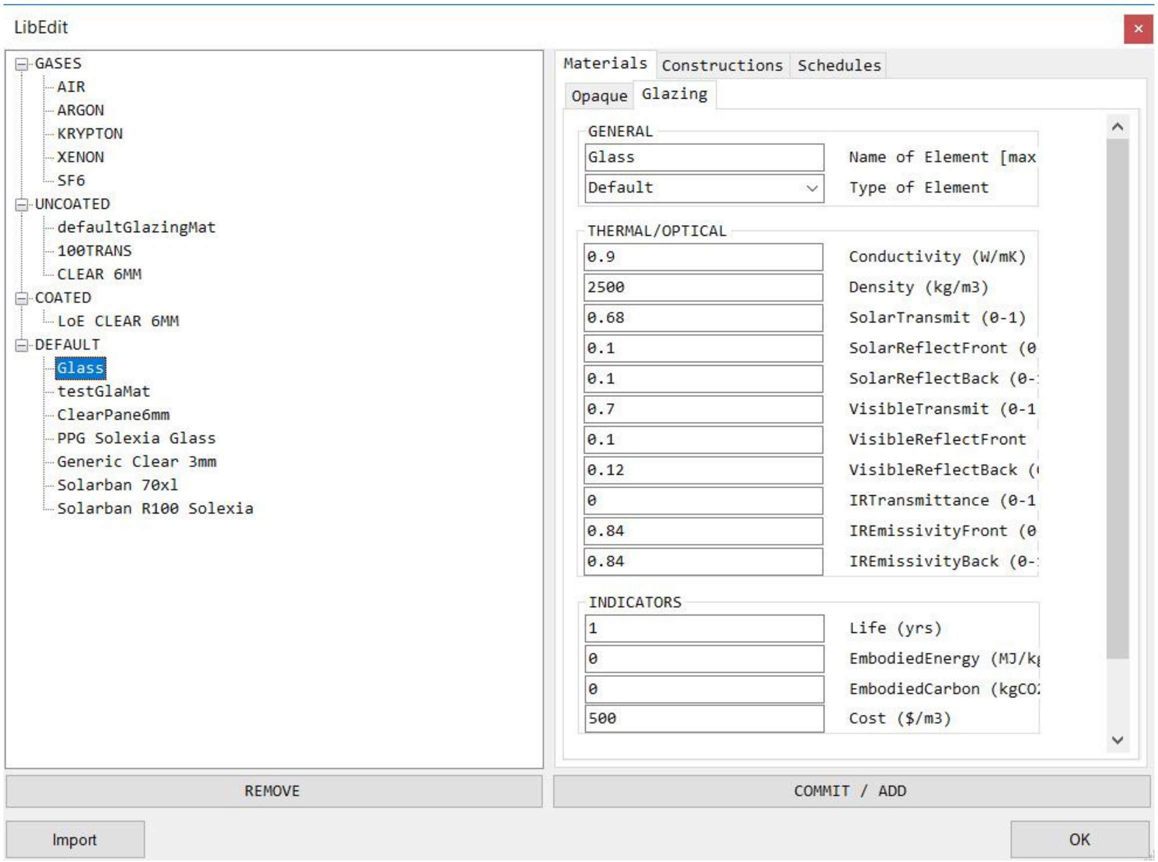

Figure 25: Material Characteristics

Every material and associated product has a list of characteristics (Figure 25) depending on whether it is an opaque or transparent material that control the performance in the ArchSIM energy model. Opaque products key characteristics for this test are: conductivity (W/mK), density (kg/m3), specific heat (J/kgK), thermal (0 - 1), solar (0 - 1) and visible light (0-1). These factors determine the level to which the surface absorbs, retains or reflects heat and it can act as an insulating material (R-Value). Transparent materials have a more complex set of characteristics due to the transmission of light and the ability for the material to reflect visible light. The key transparent factors are: conductivity (W/mK), density (kg/m3), solar (0 – 1), visible light (0 – 1) and IR emissions (0 – 1) In addition to dealing with the transmission of light, windows often act as the lowest insulating factor in a building, using the inverse of R-value to determine its insulating qualities (U-Value).

Each of the materials and products shown in Table 4 were applied to a thermal zone in a combined assembly of other materials noting the outside to the inside face. There are a total of five general assemblies plus four transparent material setups to all thermal zones. Baseline_Wall_Exterior, which consist of concrete on the exterior with a thin coating of gypsum material on the interior face of the wall. Baseline_Wall_Interior is similar to the exterior wall except the concrete is thinner and has a double coating of gypsum, one board on each side. Baseline_Roof has ceramic roofing tiles laid atop a concrete screed and supported by concrete supports. Baseline_Floor is constructed using exposed concrete ceiling top with a concrete screed and regular tiles. Baseline_Ground has the same construction of the Baseline_Floor, except a small barrier or insulating material is added beneath the concrete. Baseline_Window is a single pane of glass with no gas barrier made of low-grade glazing. Window Test Cases range from double pane to triple pane that all employ gas-filled air gaps to improve performance and based upon actual windows constructed using the polycarbonate materials (GRPU 2013).

5.1.3 Baseline and Test Case Analysis

With the parametric model created, correctly zoned and materials applied to assemblies the energy analysis model, ArchSIM and EnergyPlus, was conducted for the Baseline and the three subsequent test cases. For this analysis, all variables in the thermal zones were held constant throughout each test case, with only the window material and constructionchanged in each test. To determine the amount of CO_2 and other emissions created during the operation of the building over a year the Shanghai power grid composition was used. The local grid structure has a 57% Coal, 32% Hydro, 5% Wind and 6% other sources which equates to 1KwH equal to around 1.05Kg of CO_2 (Liu, Z. 2016) (State Grid Corporation of China 2017) (China Enegry Group 2016).

Table 5: Energy Simulation Modeling Test Case Results

Test Case	*Total Energy (KwH)*	*CO_2 (Kg)*	*EUI (KwH/m^3)*	*CUI (Kg/m^3)*	*Energy per Unit (KwH/m^3)*
Baseline	1,514,608	1,590,339	306.0606	321.3637	17,139.4
Low Grade	1,514,370	1,590,089	306.013	321.313	17,136.70
Mid Grade	1,489,707	1,564,192	301.0287	316.0801	16,857.61
High Grade	1,475,209	1,548,970	298.0992	313.0041	16,693.55

Changing a single material and product in inefficient buildings can have mixed results depending on the combination of material in question. Based upon the testing conducted Low Grade windows, with two panes of glass separated by a single layer of Argon gas, has a negligible effect on the total energy savings (222 KwH and less than a percentage of EUI savings). Both Mid Grade (Double Pane with Kypton Gas) and High Grade Windows (Triple Pane with Xenon Gas) performed well reducing the EUI by 1.7% and 2.7% respectively. A reduction in a total of 56 units that has a total effect of 445.9 KwH savings for each unit in the building at best. Based upon this a single material and product change can have a noticeable impact on buildings that are in need of renovation.

Energy Use Intesity (EUI KwH/m^3) and Carbon Use Intensity (CUI Kg/m^3) are calculated by dividing the total energy or Carbon by the square footage of the test building ($4,948.72m^2$):

$$Per\ Area\ (Energy\ or\ Carbon) = \frac{Total\ (Energy\ or\ Carbon)}{Building\ Area}$$

5.2 Logistical System Analysis

Logistical System Analysis' testing purpose was to explore the energy consumption and CO_2 emissions connected to material and product transmission in the MPBN System. Although the ideal logistics network is used, for simplicity sake and data constraints, four modified versions of the ideal network were conducted based on real-world settings and differing logistics chains. The four test cases were decentralized or centralized material and product facilities located near the final construction site; centralized facilities located far away; the material facility located the site, but the product facility located far way and finally vice versa (the material facility located far away and the product production site located neat Anshan Xincun). All test cases relied on simple trip distribution using ArcGIS moving directly from material production facility, directly to the product production facility, to one of two wholesaler locations outside of Shanghai and finally to the construction site in Shanghai.

Using these test cases the total distance was determined in kilometers (and miles) based upon the routing as determined using the Chinese road shapefiles and ArcGIS's built-in Network Analysis software. To this trucking mechanics were applied in the form of weight category, based upon the truck carrying an entire buildings material requirement at once, and fuel consumption. Trucks do not require refrigeration for the preservation of these materials and products base fuel consumption was applied, with a one hour wait time at each destination and origin point (effectively one gallon or 3.79 liters or diesel fuel). From there the MJ/L calculation was converted to KwH and CO_2 emissions to allow common units between the logistics and MPBN System analysis.

5.2.1 Logistic Model Creation

The logistical model is entirely based in ArcGIS and using three sets of shapefiles and databases: Chinese Road Shapefile, Chinese Rail Shapefile and Facility Location Data (Wu, Y. 2018). The entirety of which was not necessary forthis study, as only road network nodes from and to Guangzhou and Shanghai were of interest. As a result, the data and shapefiles were trimmed to focus on this area only and speed up calculations before the Network Analysis Nodes were created.

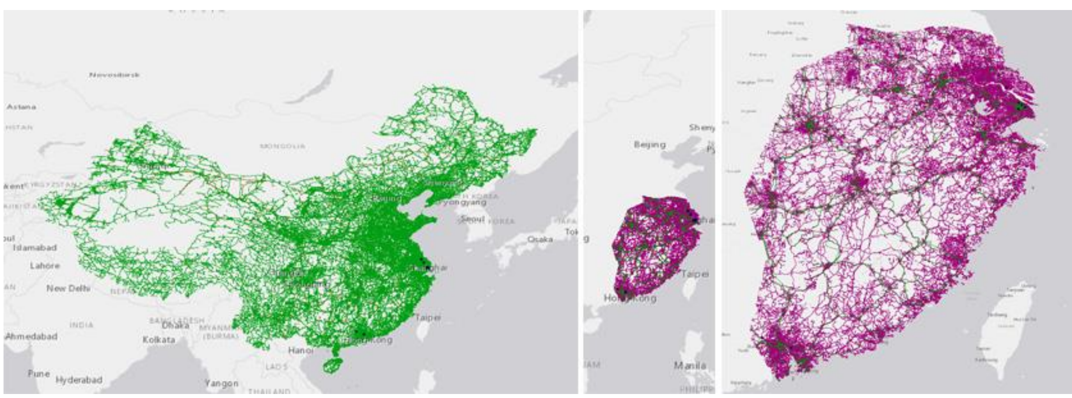

Figure 26: Chinese Logistical Road Mapping

As can be seen in the figure above the road network considered was still quite substantial, allowing a finegrain assessment of the distance between facilities. Two challenges still persist as a result of the shapefiles containing only generalized roads and highways, not the fine-grain networks inside of cities or their speed limits. To compensate for these potential issues, major facility nodes were placed as close as possible to their actual location (in the case of Anshan Xincun) and within a 100-150km circular radius around the major cities of Guangzhou and Shanghai. When using Spatial Analysis to create the routing network in

ArcGIS, the major time cost to determine routing information relied on total distance travel and the minimization of distances. As it was impossible to code and track actual speeds and travel times over such large distances and averages were assumed.

Table 6: Facility and Logistical Center Locations

Name	*Facility Type*	*Dest. Type*	*Location*
M1	Material Production	Origin	Near Shanghai
M2	Material Production	Origin	Near Guangzhou
P1	Product Production	Mid Trip Journey	Near Shanghai
P2	Product Production	Mid Trip Journey	Near Guangzhou
W1	Warehouse	Mid Trip Journey	North Shanghai
W2	Warehouse	Mid Trip Journey	South Shanghai
A	Anshan Xincun	Destination	Shanghai

Figure 27: Facility and Logistic Locations

Facility linkages were determined by ArcGIS Network Analysis and four types of connection scenarios that examined the common logistics routes present in China and the world. ArcGIS Network Analysis functions determine the shortest pathway between one point in a network and all others, or meets certain conditions. The controlling factor for this analysis is based on the minimization of distance between points while visiting only one material facility, one product facility, the closes logistic center and ultimately ending at the Anshan Xincun site. Combination of material and product facilities was determined by the four major logistic chains: Localized (close), centralized (distant) and combinations.

5.2.2 Analysis Setup and Logistic Model Database

As noted four main routing choices were examined using trucks as the primary mode of transportation: localized distribution networks (centralized or decentralized), distant distribution networks (centralized) and combination of a localized and distant facility (Covestro 2017). Localized distribution used facilities that were all located close to Shanghai for both material and product production. Distant distribution networks examined the consequences of materials and products coming from a far-away facility in the same nation (or exterior in smaller countries). Combination networks are defined as those that have a material or product facility located near the endpoint and the other located at a distance.

Table 7: Logistical Routing Network

Routing	*Type*	*Nodes*	*Length (Km)*	*Travel Mode*
Routing #1	Localized	M1, P1, W1, A	159.51	16 Ton Truck
Routing #2	Distant	M2, P2, W2, A	1,528.30	16 Ton Truck
Routing #3	Combined #1	M1, P2, W2, A	2,887.43	16 Ton Truck
Routing #4	Combined #2	M2, P1, W1, A	1,557.98	16 Ton Truck

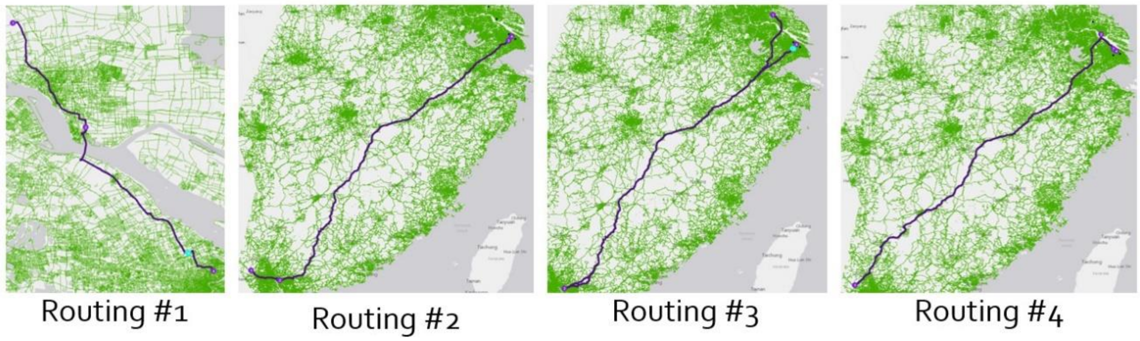

Figure 28: Routing Network Options

5.2.3 Logistical Test Case Analysis

Based upon the logistical routing lengths, as determined by ArcGIS Network Analysis, as shown in Table 8 the total energy consumption of the logistical routes can be calculated. An core assumption of the system is that there is no return trip to any facility and that the truck leaves the system having delivered its goods. The length of the trip is divided by the number of kilometers traveled on average by a truck of a gross weight of 11 tons (class 6 truck) carrying 5~6 tons of cargo that is equivalent to the weight of the truck chassis, fuel and the materials/products in transit (Environmental Protection Agency 2017). This equates to around 35 liters per 100 kilometers traveled of diesel burnt with an average energy output of 39MJ/L of diesel consumed (Transport Policy 2018). An additional four liters are added to all Fuel Usage numbers to account for a one hour wait time at each of the four destinations. When converted to KwH it is equal to 10.833 KwH/L which produces 2.64 Kg of CO_2 per liter burnt. These values are then applied to the routing lengths for each test case to get the final logistical results.

Table 8: Logistical Routing Model Energy Consumption Results

Test Case	*Routing*	*Length (Km)*	*Fuel Usage (Liters)*	*Energy (KwH)*	*CO_2 (Kg)*
Localized	Routing #1	159.51	59.8	647.8	157.87
Distant	Routing #2	1,528.30	538.9	5,837.9	1,422.7
Combined #1	Routing #3	2,887.43	1,010	10,941.6	2,666.4
Combined #2	Routing #4	1,557.98	545.3	5,907.2	1,439.6

Three distinct categories of energy consumption were identified via this testing: ideal (Localized), efficient (Distant and Combined #2) and inefficient (Combined #1) logistical patterns. Trucking systems act more linearly (under the stated testing conditions) resulting in tiers of energy consumption and pollution generation. Using the ideal transportation category energy consumption and CO_2 generation, for logistics, is minimal and accounts for 2.5% of the total energy consumption per capita of 3.1 tCE/person as reported by China in 2015 (25.234 MwH) or around 48.0% of a household electrical consumption out of 1,349 KwH/year as reported in 2010 (Wilson, L. 2013) (China Enegry Group 2016). Efficient logistic systems are a significant drop in terms of performance from ideal, but are more realistic to those actually used, accounting for 23.4% of per capita energy and 432.7% of a households annual consumption. Inefficient energy transportation systems, which are the most common in global trade economies (of which it could be worse if dealing with shipping and international trade), are the worst at 43.4% of per capita and 811.0% of annual household consumption. These results aid in the importance that logistics play in total energy consumption in construction and the need for their consideration in urban scale systems to be integrated into energy modeling of buildings and urban fabric buildings.

Chapter 6: Findings and Results

Based upon the testing and analysis a total of eight individual test cases were conducted, four logistical choice models (examining different locations and distribution networks) and four energy test case, which were then combined into a total of 13 unique complete test cases. Each of these test cases are then evaluated upon the combined EUI, total energy, CO_2 emissions and cost as compared to the baseline to determine the urban energy load for a material choice. In addition to the single building loading model of the 13 test cases evaluation of what it would cost to replace all the windows of the neighborhood in Anshan was calculated. With the single building neighborhood model being scaled up and applied to all buildings in the area as determined by the EUI applied to the total floor area.

One aspect that should be noted by the testing and combination of the energy modeling is that the numbers represent the total load of the first year alone for EUI. The logistical routing energy load would only occur during the construction and assembly of the buildings itself or to a lesser and more regular degree during the maintenance of the building. To compensate for this fact, a secondary calculation was done seeing at what point the building, though better performing materials and products, pays off the energy debt accrued during its construction.

6.1 Combined System Results

The final combined base single building base analysis of the 12 possible test cases and the no change model (baseline) are compiled together by adding the logistical energy and emissions results to each of the three unique building test cases. For this, the major factors examined are the total energy produced in the first year, energy as a ratio of the floor area and the total carbon footprint caused by the specific material and logistical solution. The table below lists each of the possible outcomes with energy given in KwH and CO_2 measured in kilograms.

Table 9: Single Building Combined Energy Simulation Results

Name	*Material*	*Logistics*	*Total Energy (KwH)*	*EUI (KwH/m³)*	*CO_2 (Kg)*
Baseline	Baseline	N/A	1,514,608	306.0606	1,590,339
Low #1	Low Grade	Localized	1,520,207.9	307.2	1,590,246.9
Low #2	Low Grade	Distant	1,520,207.9	307.2	1,591,511.7
Low #3	Low Grade	Combined #1	1,525,311.6	308.2	1,592,755.4
Low #4	Low Grade	Combined #2	1,520,277.2	307.2	1,591,528.6
Mid #1	Mid Grade	Localized	1,490,355	301.2	1,564,350
Mid #2	Mid Grade	Distant	1,495,545	302.2	1,565,615
Mid #3	Mid Grade	Combined #1	1,500,649	303.2	1,566,858
Mid #4	Mid Grade	Combined #2	1,495,614	302.2	1,565,632
High #1	High Grade	Localized	1,475,857	298.2	1,549,128
High #2	High Grade	Distant	1,481,047	299.3	1,550,393
High #3	High Grade	Combined #1	1,486,151	300.3	1,551,636
High #4	High Grade	Combined #2	1,481,116	299.3	1,550,410

The values present in Table 9 are calculated using the following equations and metrics. Total energy is calculated through the addition of the total energy from the buildings plus that of the logistic network being examined:

$$Total\ Energy = Material\ Energy + Logistics\ Energy$$

Combined EUI is the amount of total energy calculated in the table divided by the total area of the building 4,948.72m^2:

$$EUI = \frac{Total\ Energy}{Building\ Area}$$

When comparing the results from Table 9 (Combined) and Table 5 (Uncombined) the decrease in first year EUI anywhere from 1 to 1.5 points. Combined analysis of the logistical network and building energy systems reveals the importance that logistical energy consumption has in the context of the urban fabric. In the case of the Low Grade test case it makes the total energy performance, for the first annual year, worst than that of the baseline. Causing an increasing total carbon production for all, but the Localized logistics network. Mid Grade and High Grade tests reveal better results, but still jump a noticeable amount in their total energy and carbon production as compared to the base level of energy performance as determined by the EnergyPlus simulation.

Although single annual year analysis is useful for observing the single spike that results due construction it is important to consider these increases within the context of the products lifespan. For this a payoff period has to be calculated based on the above table to see how many months, if at all, the material and product change will need to remain in order to offset the energy expenditure in its transportation. Payoff is calculated by subtracting the normal energy performance (for a specific test case, Table 5) from the Baseline energy performance. This difference is the total energy saved by the new product and is divided by the total of 1st year total energy and normal energy to calculate the total number of months needed to payoff the new material.

$$Payoff = \frac{(1st\ Year\ Total\ Energy - Normal\ Total\ Enegry)}{(Normal\ Total\ Energy - Baseline\ Total\ Energy)}$$

Table 10: Single Building Energy Payoff Period and Total Consumption

Name	*Material*	*Logistics*	*1st Year Total Energy (KwH)*	*Normal Total Energy (KwH)*	*Payoff (Months)*
Baseline	Baseline	N/A	N/A	1,514,608	N/A
Low #1	Low Grade	Localized	1,520,207.9	1,514,608	32.66
Low #2	Low Grade	Distant	1,520,207.9	1,514,608	294.35
Low #3	Low Grade	Combined #1	1,525,311.6	1,514,608	551.68
Low #4	Low Grade	Combined #2	1,520,277.2	1,514,608	297.84
Mid #1	Mid Grade	Localized	1,490,355	1,489,707	0.31
Mid #2	Mid Grade	Distant	1,495,545	1,489,707	2.81
Mid #3	Mid Grade	Combined #1	1,500,649	1,489,707	5.27
Mid #4	Mid Grade	Combined #2	1,495,614	1,489,707	2.84
High #1	High Grade	Localized	1,475,857	1,475,209	0.19
High #2	High Grade	Distant	1,481,047	1,475,209	1.77

Table 10 (continued)

High #3	High Grade	Combined #1	1,486,151	1,475,209	3.33
High #4	High Grade	Combined #2	1,481,116	1,475,209	1.79

Table 10 examines the different payoff periods for each of the 12 test cases with most of the test cases, aside from Low #2, Low #3 and Low #4, viable in terms of energy consumption. Low #2, Low 3 and Low #4 all take over 294 months (Low #3 taking 551 months) or a total of 24+ years to pay back the initial energy investment caused by the logistical route and not including yearly maintenance, material denigration and upkeep (which are not considered in this analysis but have a noticeable effect on long term energy consumption). Low #1 performs better, but still takes nearly three years to pay back the initial energy under the best conditions of a localized logistical support routing. Practically speaking low grade windows are unlikely to pay for themselves in terms of energy savings when other factors are considered in a more complete system analysis. Mid and High testing show better results with times between less than a week (for High #1 and Mid #1 using localized logistical routing networks) and upwards of around half a year at max to pay back the 1st year energy investment. The difference of between 6,000 and 10,000 on average KwH in the first year contributing to a small, but noticeable amount of time in order to offset the logistical routing, in the most realistic logistical options.

Even though the worst performing model for Mid #3 and High #3 only take less than half a year to payoff the 1st year energy investment it is important to note that this analysis only considers one material chain and no maintenance or material degradation. Most products are constructed of several materials that are made from a multitude of resources each of which would only serve to increase the payoff period in the most used logistical model. Material degradation would also worsen the payoff period as materials and products become less effective overtime resulting in less energy savings each year. Finally, maintenance would be required on each window costing time and resources and potentially addition truck shipments to be made to the site for just the building, not counting inhabitant delivery requests. The combined effects of a single material and product chain cause a noticeable effect in total energy consumption, a complex complete energy analysis of a complete urban system will only result in further worsen the payoff period and showing a more accurate evaluation of material and logistic networks.

6.2 Neighborhood System Findings

Anshan Xincun neighborhood analysis is conducted based upon a simplification of the neighborhood to its simplest metric and applying the neighborhood modeled building across this metric. Anshan Xincun is constructed of multiple blocks each with their district number, for this study, a single block district is examined. Each district is comprised of around 58 buildings ranging in bay size and floor count. Based upon satellite imagery and Baidu street view there are a total of 116 bays and 406 floors in the area highlighted in Figure 27

Figure 29: Neighborhood Layout

Using the assumption that there is a total of 116 bays arranged into an average 406 floors in the neighborhood resulting in a total area equal to 287,025 square meters (3,089,511 square feet). To determine the total energy consumption at the neighborhood level the EUI of the test is multiplied by the total floor area. The total energy consumption is then multiplied by the Shanghai power grid to calculate the amount of CO_2 produced to power the buildings. The scaler equations are broken down into two areas: building modeling and logistical model. Building modeling applies the EUI (and CO_2 Area) value of the individual test cases found on Table 5 to the total built area to scale the total Energy and CO_2 production up to the neighborhood scale:

$$Neighborhood\ Total = Per\ Area\ Evaluation * Total\ Built\ Neighborhood\ Area$$

Logistical modeling employs the total number of buildings to calculate the total kilometers traveled in order to supply the total amount of windows needed to redevelop the area. This requires multiple the length of each routing trip by the number of buildings:

$$Neighborhood\ Routing\ Length = Trip\ Length * Number\ of\ Buildings$$

Following the scaling factors the equations used to evaluate the logistics and building model, from Chapter 5, are applied as usual resulting in the Neighborhood Total Energy Consumption found on Table 11.

Table 11: Neighborhood Total Energy Consumption

Name	*Material*	*Logistics*	*Total Energy (KwH/m^3)*	*EUI (KwH/m^3)*	*CO_2 (Kg)*
Baseline	Baseline	N/A	87,847,276	306.0606	92,239,660
Low #1	Low Grade	Localized	87,868,692.7	306.1	92,233,656.5
Low #2	Low Grade	Distant	88,169,711.5	307.2	92,307,012.7
Low #3	Low Grade	Combined #1	88,468,605.9	308.2	92,379,851.2
Low #4	Low Grade	Combined #2	88,176,238.6	307.2	92,308,603.3
Mid #1	Mid Grade	Localized	86,438,070	301.2	90,731,679
Mid #2	Mid Grade	Distant	86,739,089	302.2	90,805,036
Mid #3	Mid Grade	Combined #1	87,037,983	303.2	90,877,874
Mid #4	Mid Grade	Combined #2	86,745,616	302.2	90,806,626
High #1	High Grade	Localized	85,597,228	298.2	89,848,788
High #2	High Grade	Distant	85,898,247	299.3	89,922,144
High #3	High Grade	Combined #1	86,197,141	300.3	89,994,983
High #4	High Grade	Combined #2	85,904,774	299.3	89,923,735

By using the scaler factor, instead of a complex model analysis, certain values are most likely suppressed and creates a more generalized evaluation of the neighborhood analysis. However, despite this what is evident is the large amount of energy that is consumed within the neighborhood context and that smaller gains have slightly less of an impact (whether this is due to the scaler factor or an observed problem would require further testing) due to the massive amount of energy involved. That even the best case scenario of High #1 saves nearly 2,000,000 KwH in the first year when accounting for logistics, the equivalent of 1.33 entire old baseline buildings.

Table 12: Neighborhood Total Energy Payoff

Name	*Material*	*Logistics*	*1st Year Total Energy (KwH)*	*Normal Total Energy (KwH)*	*Payoff (Months)*
Baseline	Baseline	N/A	N/A	87,847,276	N/A
Low #1	Low Grade	Localized	87,868,692.7	87,833,614	30.81
Low #2	Low Grade	Distant	88,169,711.5	87,833,614	295.20
Low #3	Low Grade	Combined #1	88,468,605.9	87,833,614	557.73
Low #4	Low Grade	Combined #2	88,176,238.6	87,833,614	300.93
Mid #1	Mid Grade	Localized	86,438,070	86,402,991	0.29
Mid #2	Mid Grade	Distant	86,739,089	86,402,991	2.79
Mid #3	Mid Grade	Combined #1	87,037,983	86,402,991	5.28
Mid #4	Mid Grade	Combined #2	86,745,616	86,402,991	2.85
High #1	High Grade	Localized	85,597,228	85,562,149	0.18
High #2	High Grade	Distant	85,898,247	85,562,149	1.76
High #3	High Grade	Combined #1	86,197,141	85,562,149	3.33
High #4	High Grade	Combined #2	85,904,774	85,562,149	1.80

Table 12 applies the neighborhood scaler results from Table 11 to the equations used in Section 6.01 in the creation of Table 10 to evaluate the neighborhood payoff of each of the 12 test scenarios. In most cases, as noted with the previous analysis, many results are similar as a potential result of applying a scaled analysis rather than an independent neighborhood analysis in Rhino/Grasshopper. Still the payoff period can be seen to change towards the more extreme values due to the increased energy consumption at the neighborhood scale. In the most inefficient logistical systems the total energy difference between the 1st year total energy and the normal total energy is equivalent to half that of a single building in the neighborhood.

In general, the findings of the neighborhood analysis support the importance of logistical evaluation of support and supply systems in the urban fabric and the value that comes from combining it with the MPBN System. As products are often comprised of multiple materials and real world logistical paths are more complex than the simplistic model employed throughout this research and would increase the 1st year energy cost and the total payoff period if fully considered. Future iterations of this process should examine tradeoffs, multiple logistical pathways and better neighborhood modeling to improve the benefit that can be achieved through logistical and building energy modeling combinations.

Chapter 7: Conclusions

The primary research objective of this paper was to examine the effect that an integrated model of logistical (ArcGIS) modeling combined with building energy modeling (Rhino/BIM) could contribute to understanding the costs, energy consumption and emissions of a complete supply chain in the context of an MPBN system applied to a single material. To develop a more accurate model of energy consumption, in relation to urban systems, and consumption patterns when building or redeveloping buildings and infrastructure. To explore the relationship often overlooked by building energy modeling that the transmission and flow of materials and resources in the urban context is required to produce and maintain the modern way of life that many take advantage of. As such the findings of this paper that examining a material, and its alternatives, within the greater context (going through all elements focused on during the study) can lead to lower emissions, better energy use, and a more accurate picture of the costs caused by a particular material applied to an urban context. Within the experimentation of Anshan Xincun in Shanghai China test case, but whose general findings and system analysis has applications outside of this specific test case.

Through the implantation of the research methods and analysis explored throughout this study three major take away can be gleamed.

- *Logistical importance in urban systems when considering system effects in energy and carbon consumption:* The consideration of a single material routing line had a noticeable effect on the total energy consumption at the building and neighborhood level. That a single material following the efficient or inefficient logistical pathways contributed several months to the total consumption payoff period. An effect that is likely to increase the more material are considered and more accurately modeled using this combined approach.

- *Combined system analysis gives better insight into urban systems than isolated evaluations of individual sections:* Linked system analysis can lead to better and more accurate evaluation of urban systems than traditional methods which consider these parts in isolation.

- *Further research is needed to better simulate and understand the complex nature of urban systems in how they form a large system of systems network:* The research conducted here serves as an initial test case and framework creation for a system that requires additional refinement to better create urban outcomes by complex combined system analysis. Further research is needed to expand and evaluate the effect it can have as a practical tool for urban energy and carbon analysis in connected systems.

A key future objective of this research and the logistical linkage with building modeling is to eventually develop a practical application and system that could be of use to current practitioners involved with the built environment. Through the application of various costing or payoff metrics (energy, CO_2 emissions, carbon productivity, distance, time and monetary cost) one could automatically compare alternatives using the systems algorithms to determine the best supply chains and logistic products to purchase to meet their goals. The objective would be to create a design space and trade offer between different costs and allow the user to define the best outcome for themselves, while still considering other elements. By applying GIS the system itself could appear and function as a Google Maps like software for the transportation and selection of resources, materials and products within the urban context.

Although the practitioners interactive and integrated system is a key future objective the present research can be applied as a preliminary test case for use by the Shanghai Government in an evaluation of its current housing stock. The energy testing and logistical analysis conducted over this paper show initial energy savings in one small subset of the large homogeneous house stock of Worker Villages that are, at present, are highly inefficient to heat, cool and use. Future iterations of testing can reveal better material and product interventions for meeting the goals outlined by their 2035 plan. With the current and future iterations possibly informing policies and large scale decision making processes that involve the built and logistical environment.

Several issues are present in the current iteration of the combined Logistics and MPBN system combined nation data constraints, system boundaries, maintenance/life cycle, data requirements, multiple material consideration and a simplification of the system that would allow its more practical and commercial application. At present the data that is often required to conduct a more in-depth and specific data analysis requires the cooperation with material and product suppliers, in addition to logistical companies, without this, only generalized conclusions can be derived. Which for general initial analysis at the macro urban scale may be sufficient but inhibits finegrain analysis. Delineating the system boundary of the MPBN system can be difficult at times to properly consider all materials and options concerning material production and product fabrication. Future iterations may include the active consideration of resource procurement and refinement as a part of this urban flow. Maintenance and lifecycle analysis is not currently considered, but is of key importance to payback and occupancy usage rates that may have a large effect on the total energy consumption and payback rate of the system. Linked with these three previous issues is the problem of data requirements and the large number of variable required to conduct this analysis at present. Ideally, the system needs to consider multiple material pathways in the logistics and product fabrication model, as even glazing was simplified for this analysis to the single piece of glazing rather than all materials used in the construction of the window. All of which should be compacted into a software and structure that could be applied in practical settles to have a direct impact on the logistics chain, in addition to noting the large impact these combined nested systems have when considered alongside each other, instead of in isolation.

Carrying this work forward several steps should be taken to address key concerns and limitations of this model and expand the usefulness of the models to better represent actual logistical and energy systems. Further iterations of the MPBN and Logistical linkage should consider multiple material pathways that compare energy costs with monetary costs to evaluate material choice analysis in the production of final products. Controlling for the cost of goods in terms of dollars and the cost incurred to the earth through the consumption of energy and generation of pollution. Consideration needs to also be given to the creation of carbon and its potential recapture and reuse as a resource as a model for Carbon Productivity of urban scale systems. Both Logistical and Building modeling (especially neighborhood evaluations) need to be expanded to better represent real world conditions while simplifying where necessary. Overall this initial study adequately explored the importance of linking logistical systems with the MPBN system and the built environment to show that careful consideration of complex systems is necessary to explore the effect that these systems of systems have on the urban condition. These ideas warrant further exploration to better aid in the targeting of system improvements as a means of reducing the carbon impact and energy consumption in large scale interconnected urban systems.

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